

# New Tools for Precision Neutrino Interferometry

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April 4, 2011

- What are neutrinos ? Why study them ?
- Interference in neutrino beams.
- Neutrino Properties from recent experiments with natural and man-made sources
- New generation experiment

slides from many experiments  
esp: SK, SNO, Kamland, Minos



Will not talk about Daya Bay and LENS



# What is the scientific interest in neutrinos ?

FERMIONS			matter constituents spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	$(0-0.13)\times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_M$ middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_H$ heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

- ~15 yrs ago all neutrino masses were thought to be 0 and all neutrino flavors distinct.

- With new discoveries a distinct, unexpected pattern has emerged.

- Science of neutrinos has deep connections to understanding of matter, cosmology, and astrophysics.
- Existence of neutrino mass itself is physics beyond the standard model because of the left/right properties of the neutrino as well as the smallness of the mass. It implies a new mechanism for mass generation in which neutrinos are their own anti-particles.



# Basic Interactions of neutrinos

All the particles of a given kind are identical.

All **electrons** are absolutely identical.

**Electrons** do not have birthmarks.

But there are 3 kinds, or flavors, of electron-like particles:

<u>Particle</u>	<u>Symbol</u>	<u>Mass</u>	<u>Associated Neutrino</u>
Electron	$e$	1	$\nu_e$
Muon	$\mu$	200	$\nu_\mu$
Tau	$\tau$	3500	$\nu_\tau$

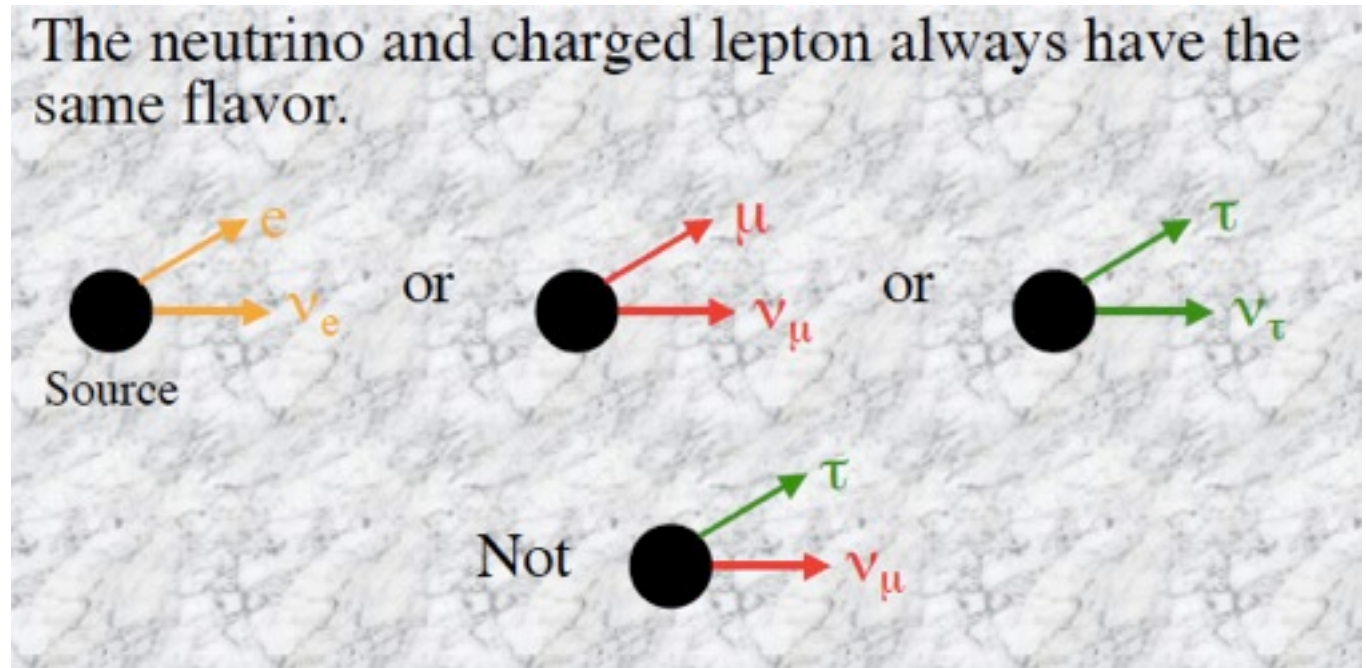
Charged  
leptons

Neutrinos or  
neutral leptons

Neutrinos are always produced or destroyed in association with their charged partner with the Weak interaction.



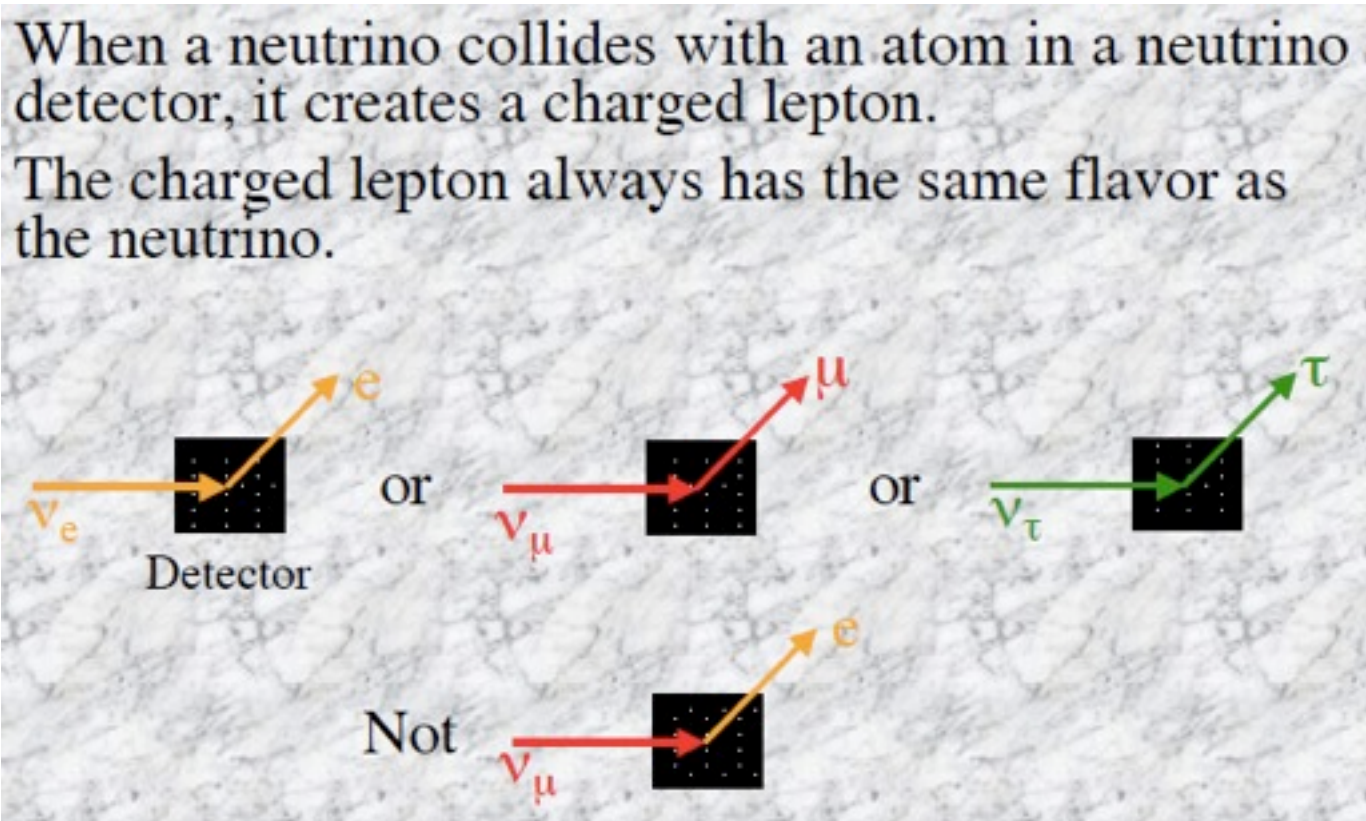
## Creation



## Detection

These are called “Charged current” interactions in which neutrino changes electrical charge.

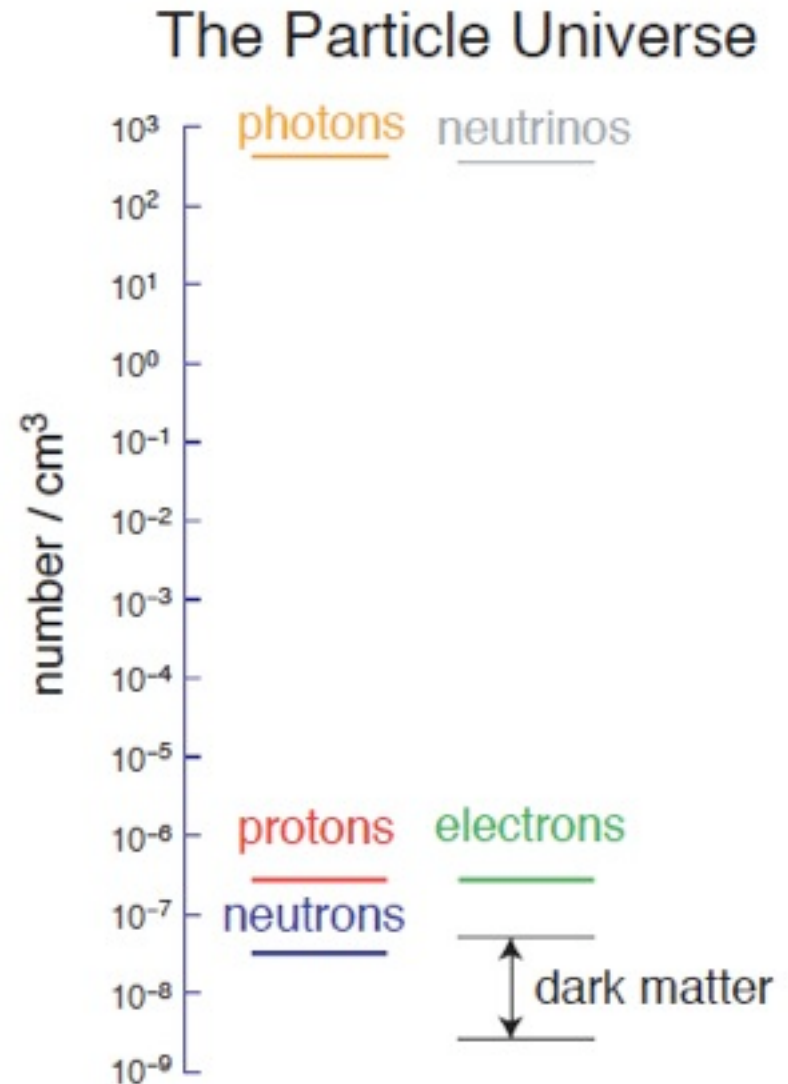
There are also “neutral current” interactions in which a neutrino has an elastic interaction that leaves observable energy in detector.





# Neutrinos in Cosmology

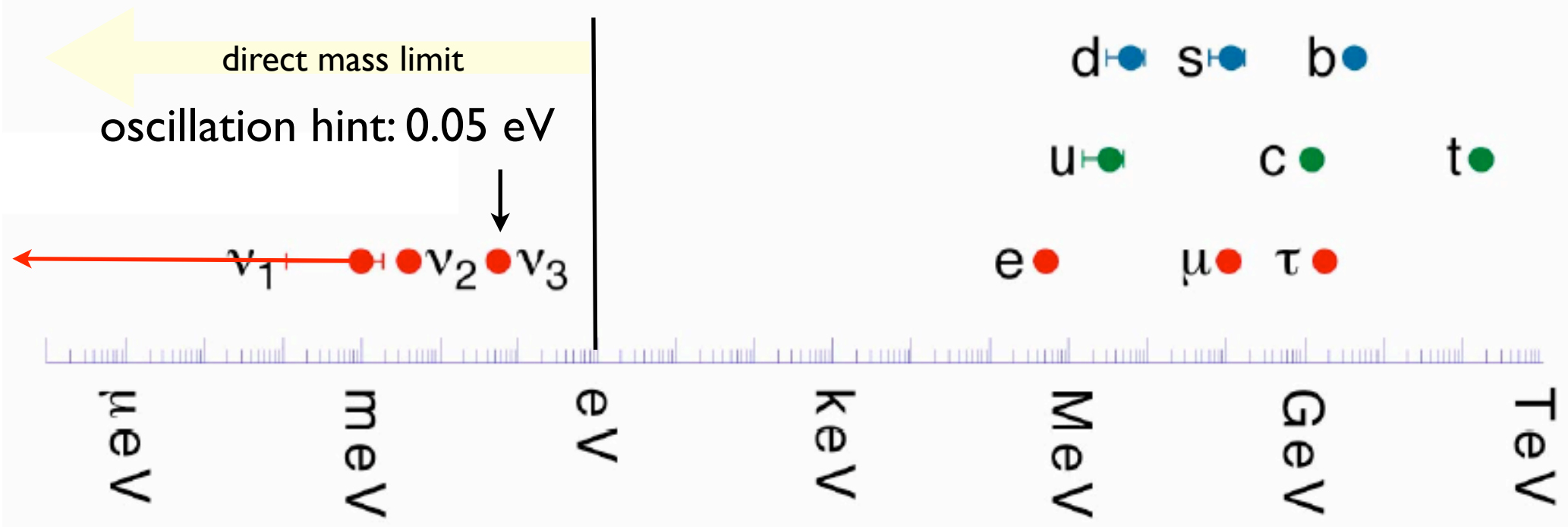
- The most abundant particle is the photon:  $\sim 400/\text{cc}$
- The most abundant matter particle is the neutrino at  $56/\text{cc}$  of each type.
- CNB (1.95K) is a relic of the big bang similar to the CMB (2.725K). Neutrinos decoupled at 2 sec while photons decoupled at  $\sim 400,000$  yrs.





Current picture of neutrino masses points to another mass generation mechanism.

fermion masses



Mass is a coupling of the left and right components of the Fermion field, unless it is a neutral fermion in which case mass can couple fields of same handedness.



# Why Mass could imply Lepton number violation ?

	Particle	Anti-particle
Left	$(e \quad \nu)_L$	$\overline{(e \quad \nu)_L}$
Right	$e_R \quad \nu_R$	$\bar{e}_R \quad \bar{\nu}_R$

Not in SM

- Standard model has only left handed leptons in isospin states. But if neutrino has mass it can become right handed.
- If  $\bar{\nu}_L = \nu_R$  (Majorana) then neutrinos are their own antiparticles and can annihilate themselves thus destroying L.



If neutrinos have mass; the massive states need not be the same as the Weak interaction states.

This will lead  
to interference  
effects

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_a(t) = \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t)$$

$$\begin{aligned} P(\nu_a \rightarrow \nu_b) &= |\langle \nu_b | \nu_a(t) \rangle|^2 \\ &= \sin^2(\theta) \cos^2(\theta) |e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

Sufficient to understand most of the physics:

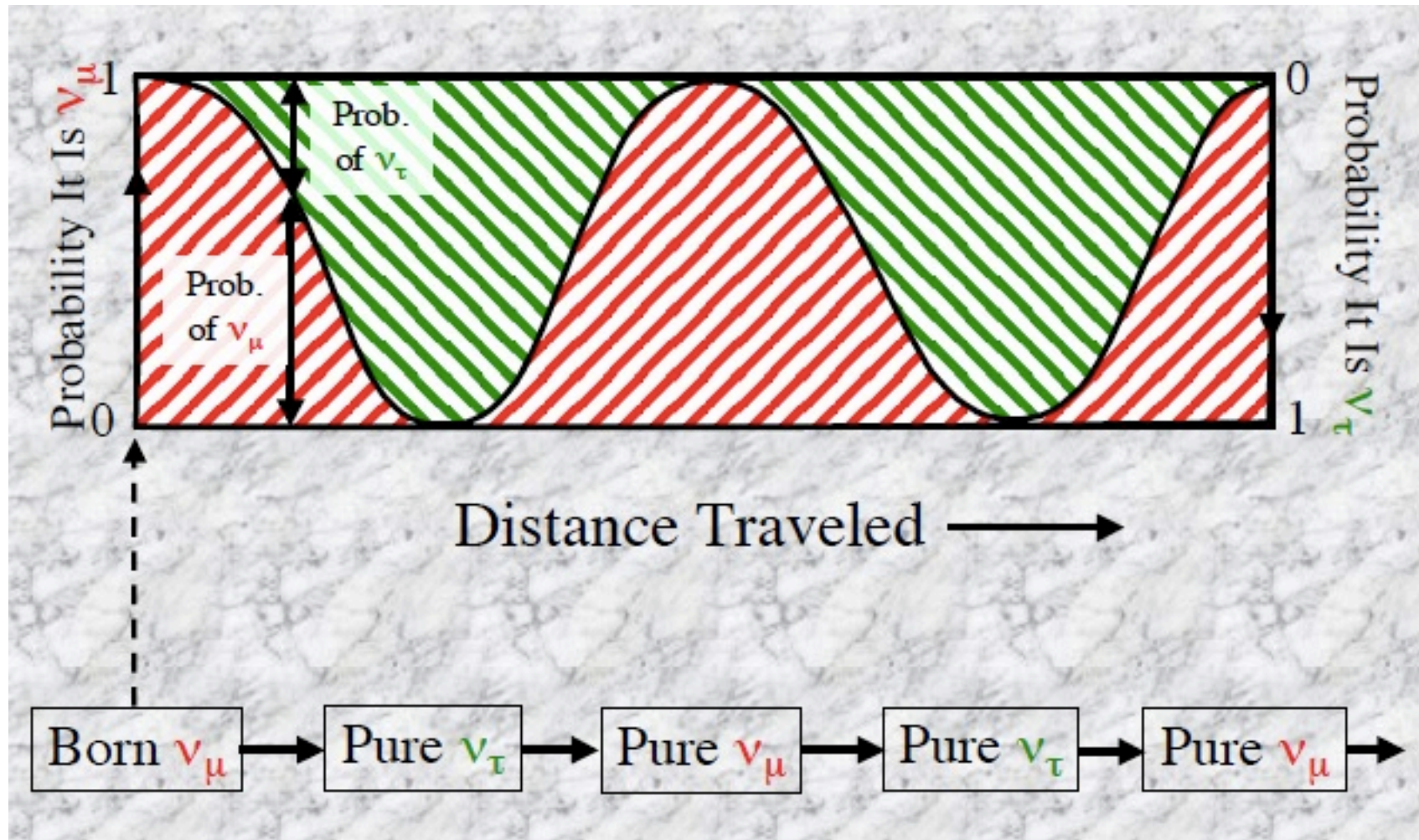
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at  $\pi/2, 3\pi/2, 5\pi/2, \dots$  ( $\pi/2$ ):  $\Delta m^2 = 0.0025 eV^2$ ,  
 $E = 1 GeV$ ,  $L = 494 km$ .



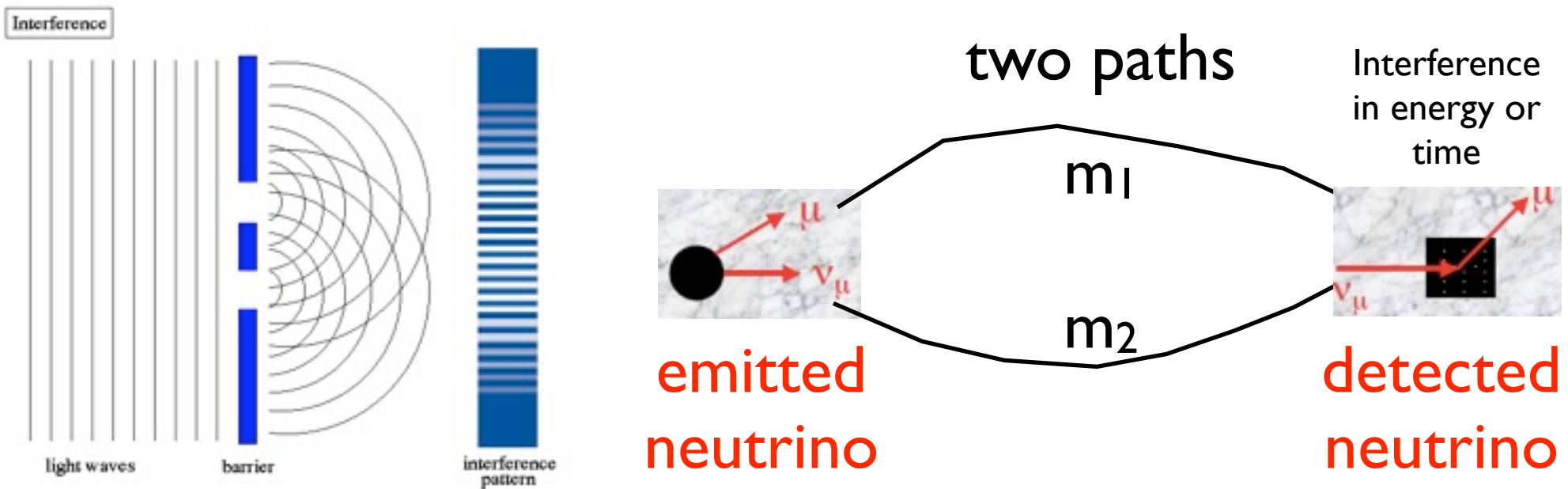
# Picture with $\theta = 45$ deg



Astonishingly this is reality



# Oscillations is a new interferometry.

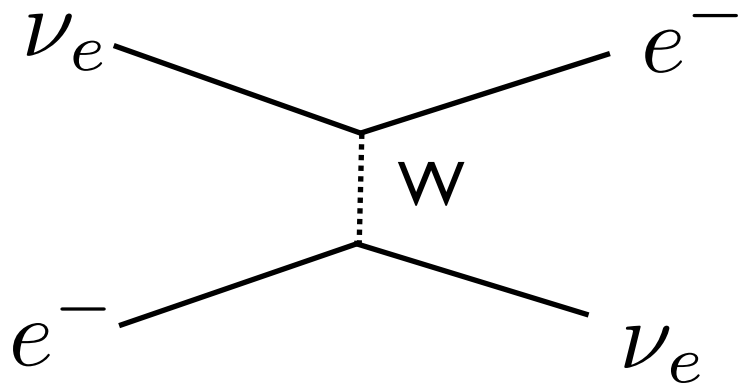


- Just as classic optical interferometry has led to new precision, neutrino interferometry has potential to be sensitive to new scales.
- e.g. Measure extremely small masses or interactions.

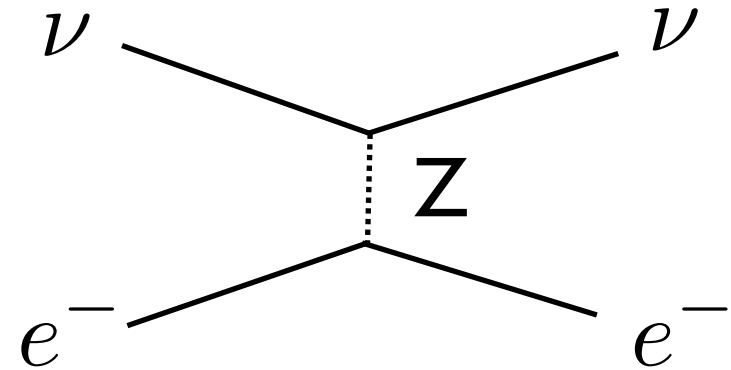


$$i \frac{d}{dx} \nu_f = H R_\theta \nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.



Charged Current  
for electron type only



Neutral Current  
for all neutrino types

Additional potential for  $\nu_e$  ( $\bar{\nu}_e$ ):  $\pm \sqrt{2} G_F N_e$

$N_e$  is electron number density.

An example of how additional phases come into the interferometry.



## Oscillations in presence of matter

$$i \frac{d}{dx} \nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{4E} \left( R_\theta \begin{pmatrix} m_2^2 - m_1^2 & 0 \\ 0 & m_1^2 - m_2^2 \end{pmatrix} R_\theta^T + 2E \begin{pmatrix} \sqrt{2} G_F N_e & 0 \\ 0 & -\sqrt{2} G_F N_e \end{pmatrix} \right) \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (3)$$

Looking at conversions of muon to electron neutrinos.

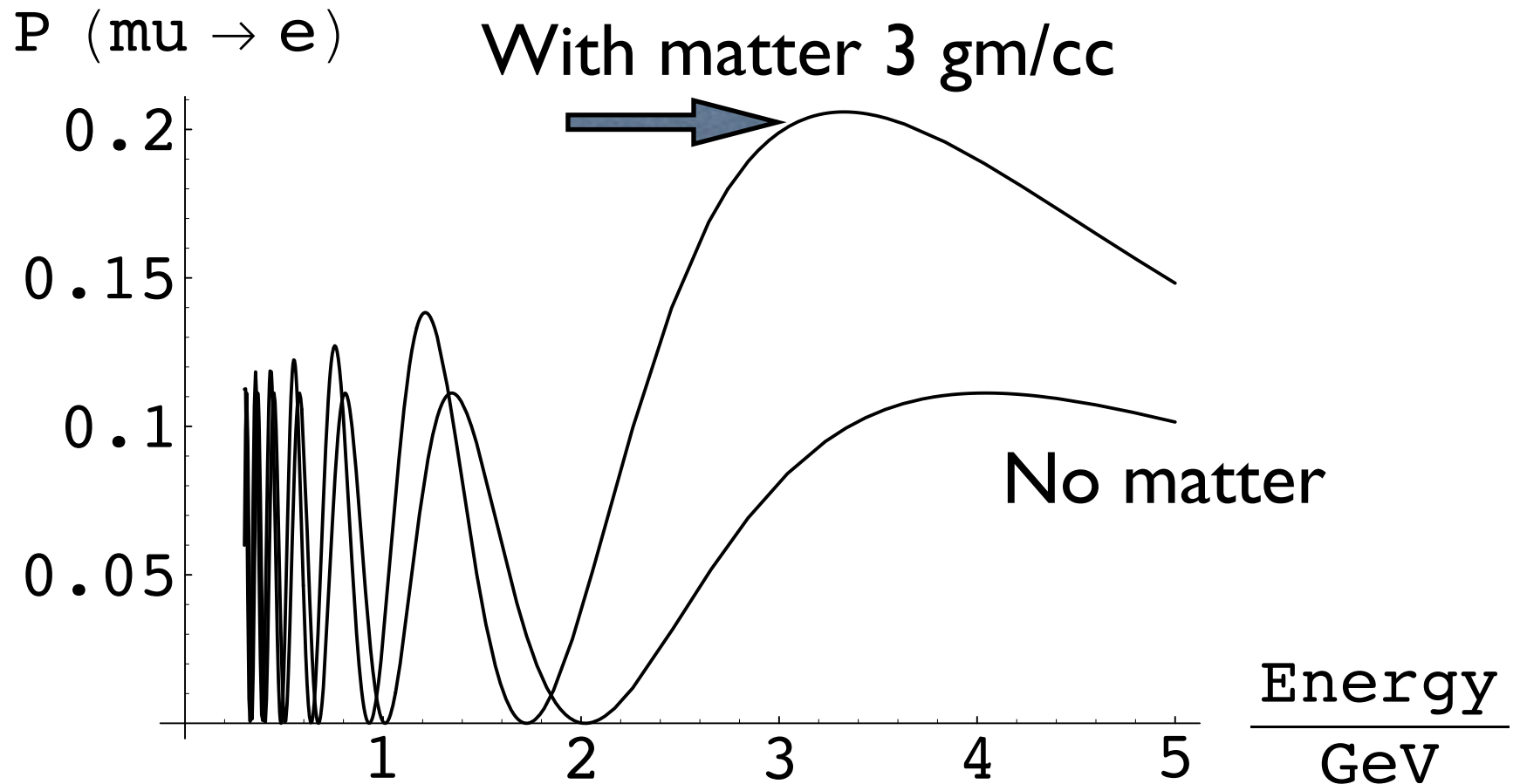
$$P_{\mu \rightarrow e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta} \times \sin^2 \frac{L \Delta m^2}{4E} \sqrt{(a - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\begin{aligned} a &= 2\sqrt{2} E G_F N_e / \Delta m^2 \\ &\approx 7.6 \times 10^{-5} \times D / (gm/cc) \times E_\nu / GeV / (\Delta m^2 / eV^2) \end{aligned} \quad (4)$$

This effect present if electron neutrinos in the mix



# 2-neutrino picture



Osc. probability:  $0.0025 \text{ eV}^2$ ,  $L = 2000 \text{ km}$ ,  $\Theta = 10^\circ$



# So far.

- 3 types of neutrinos
- Still many unknowns about these particles, but they play an important role in the early universe as well as current astrophysical processes.
- If they have mass there are fundamental consequences.
- In next slides I will review the complete picture of the 3 neutrinos: masses and mixing.

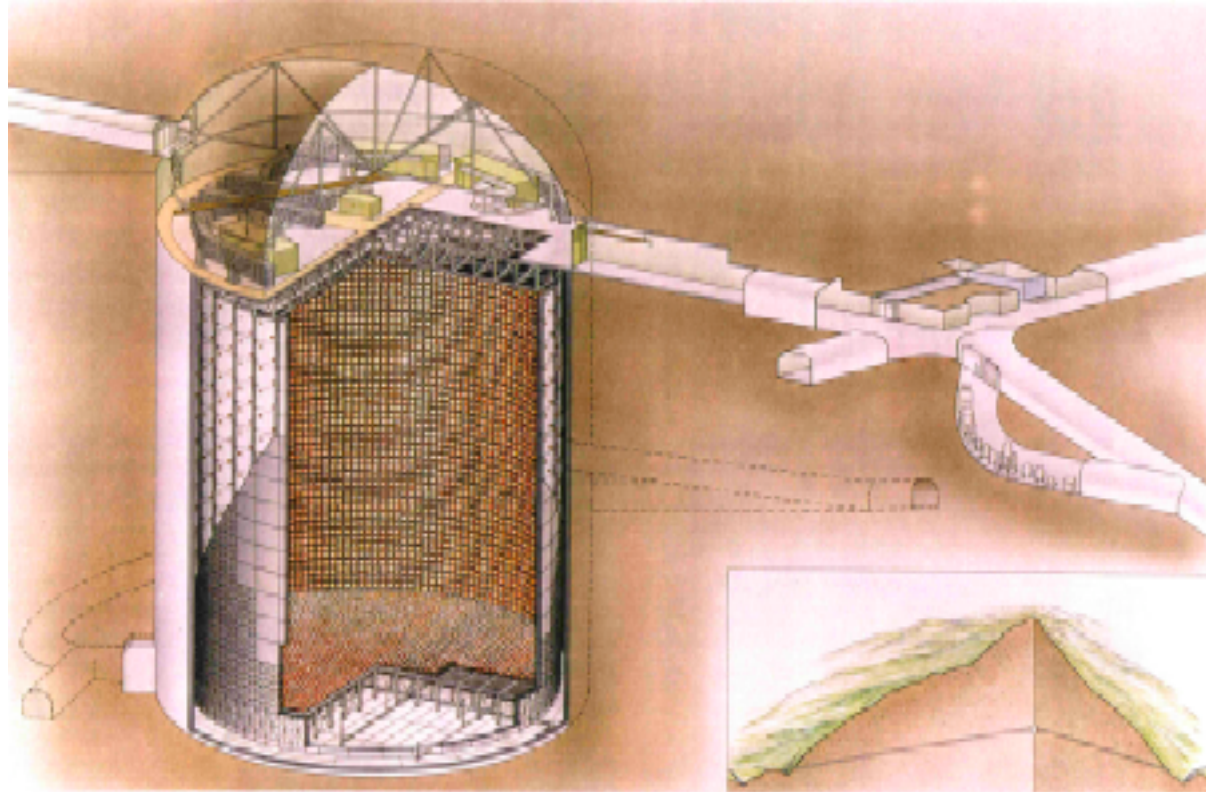


# Key new evidence

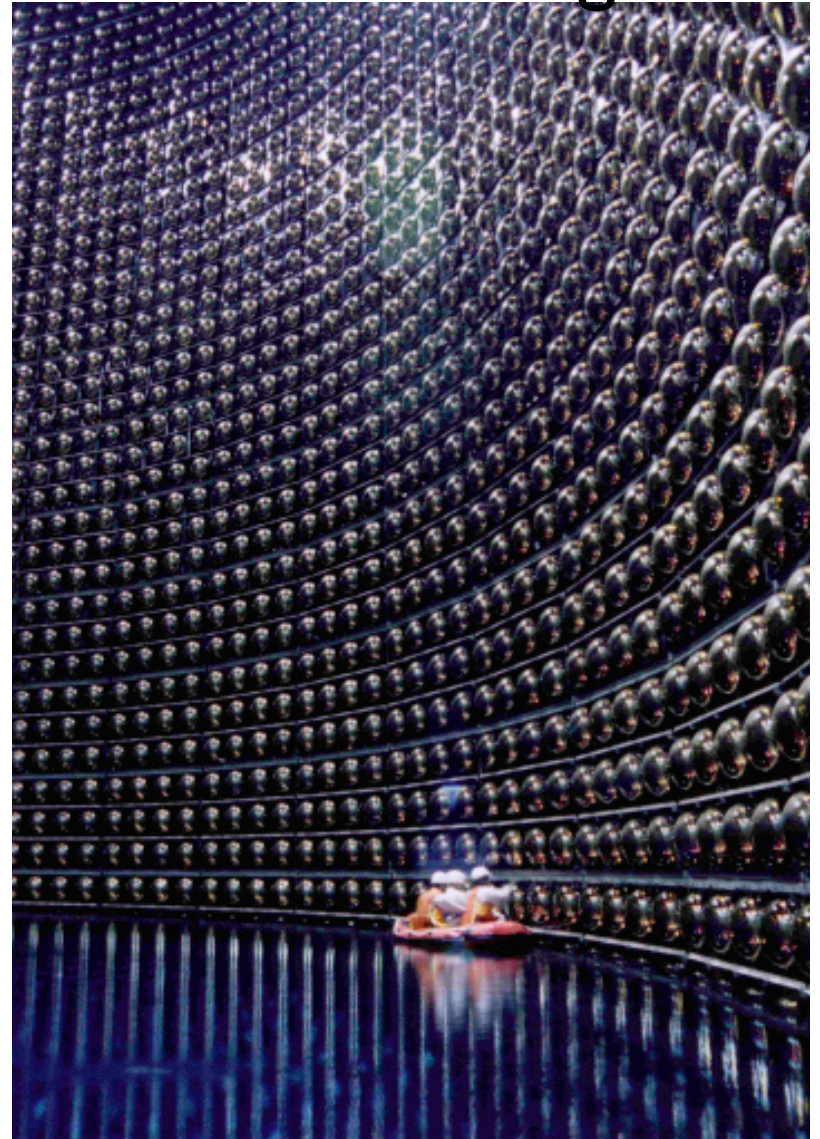
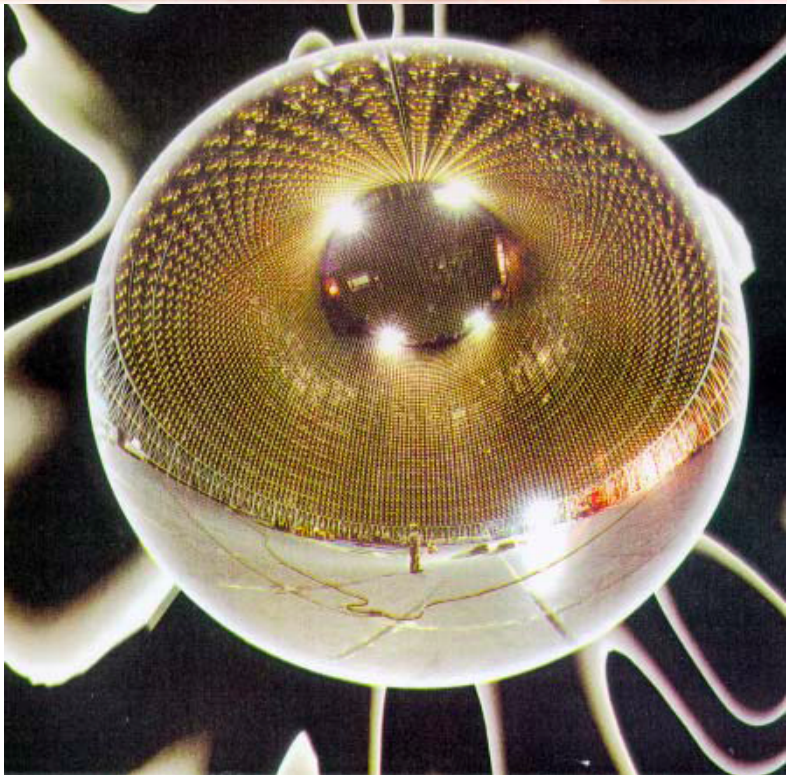
- Super KamiokaNDE (SK): observe atmospheric neutrinos.
- Sudbury Neutrino Observatory (SNO): observed solar neutrinos.
- KAMLAND reactor experiment
- MINOS accelerator beam experiment

Apologies to many other pioneering experiments





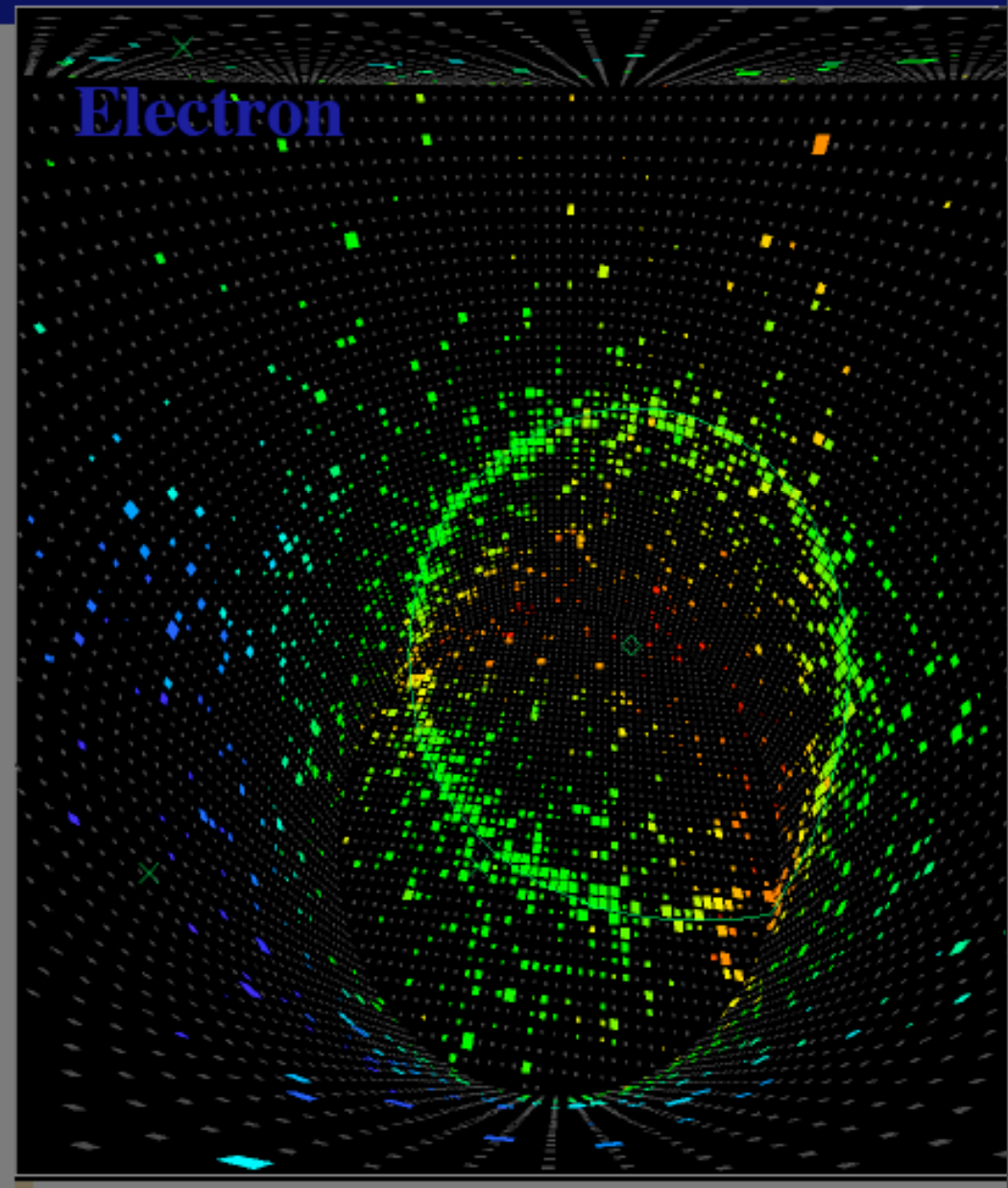
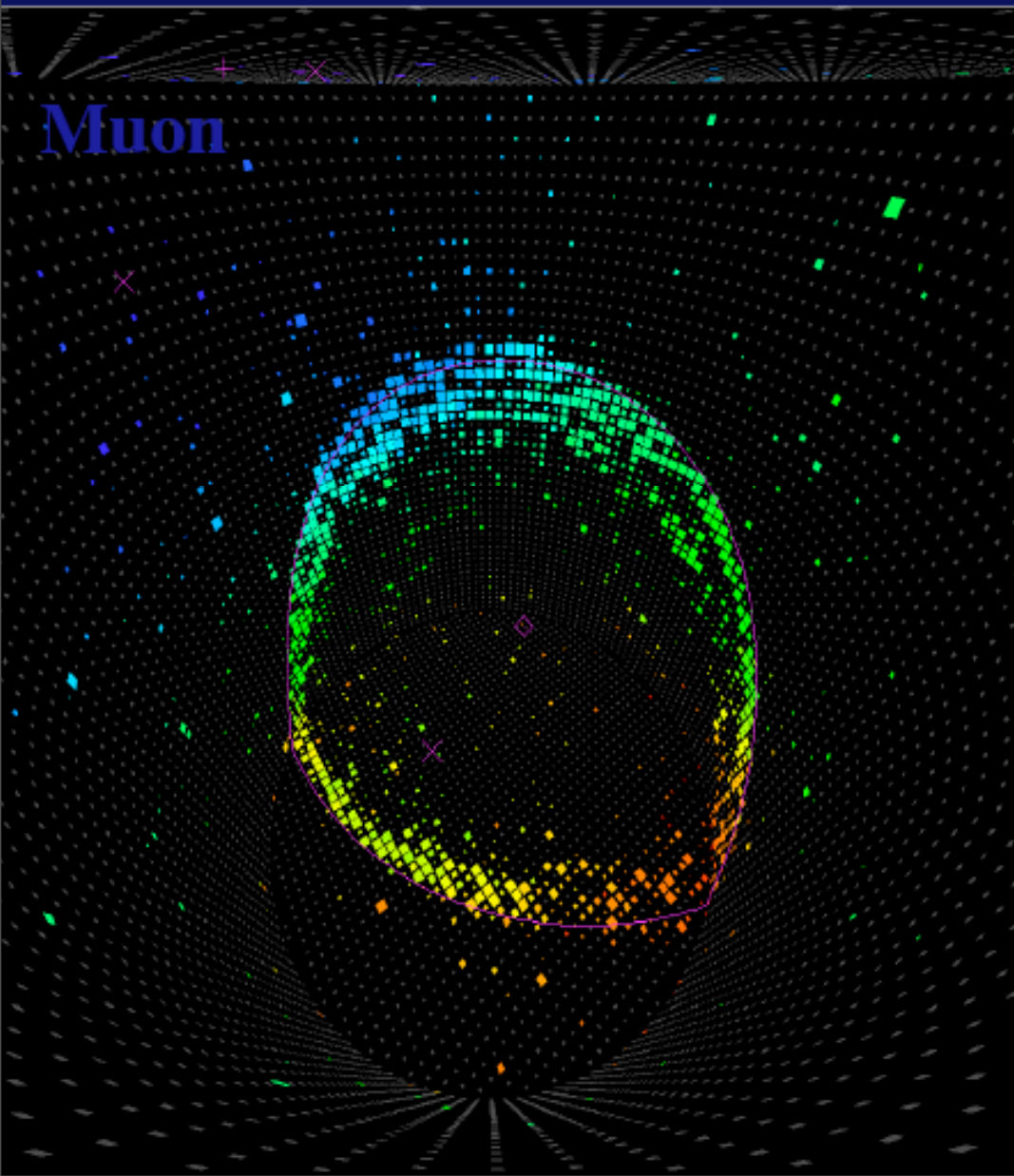
SuperKamiokaNDE  
50,000 tons of water  
11000 photomultipliers  
Cherenkov light





# Particle Identification

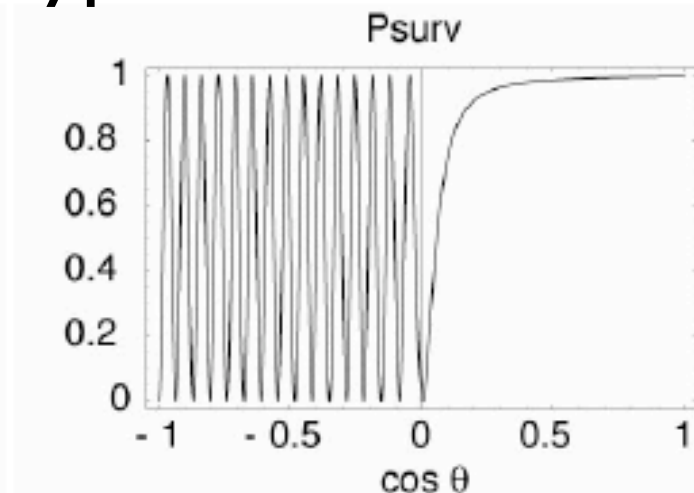
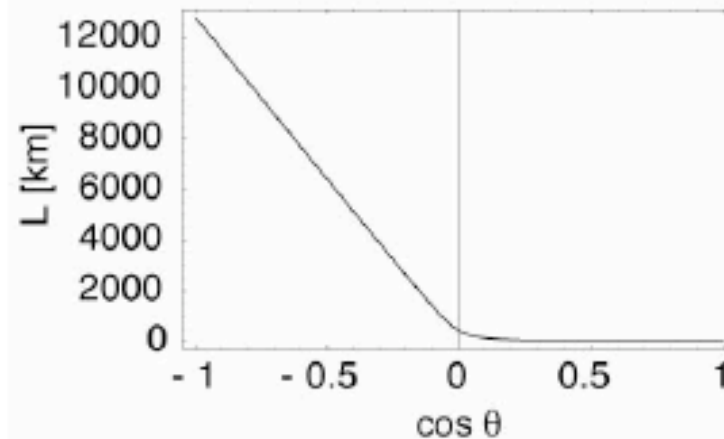
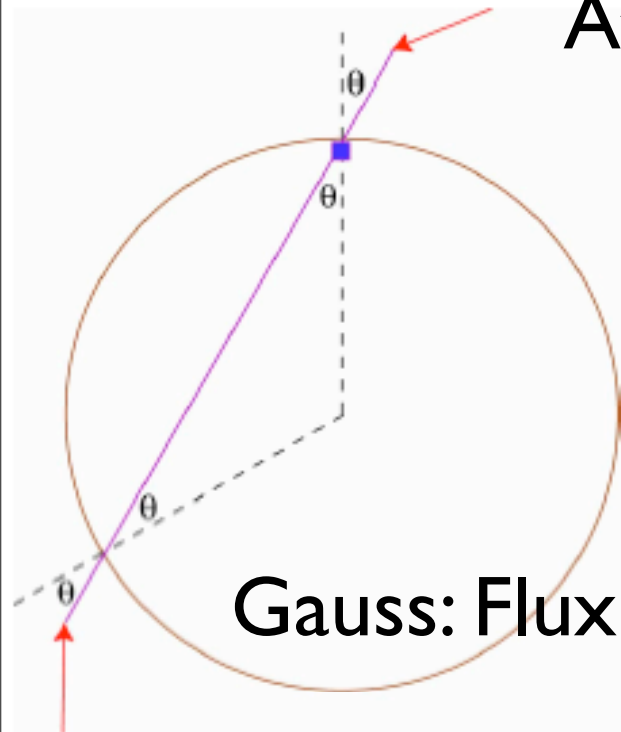
6 detected photons per MeV for fast particles



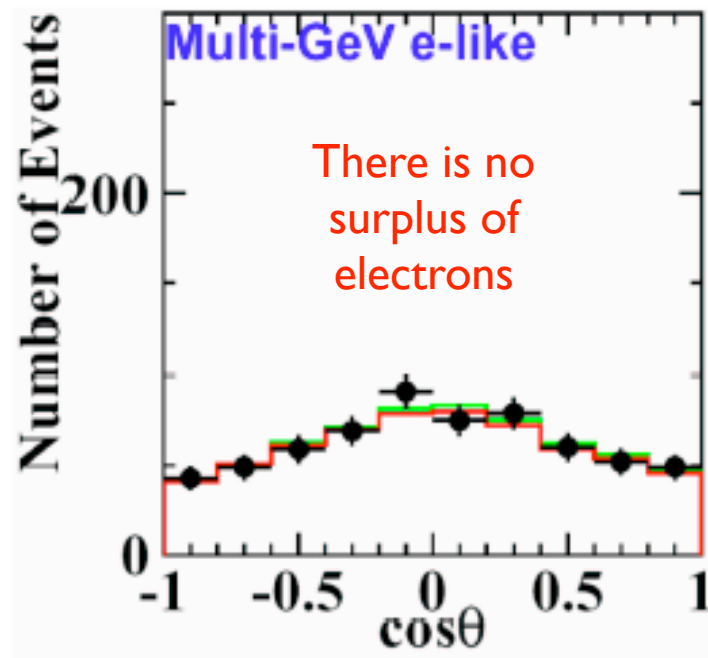


# Atmospheric neutrinos as a source for oscillation experiments

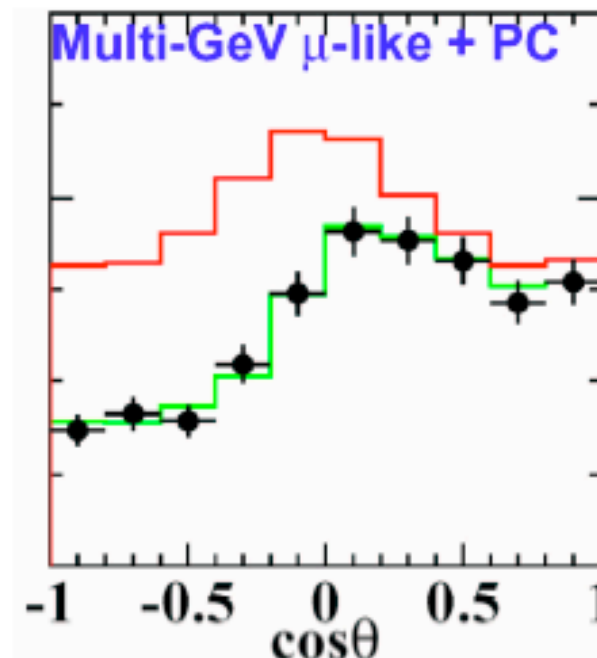
## Atm. neutrinos 2:1 $\mu$ :e type



Gauss: Flux inside spherical shell isotropic



There is no surplus of electrons

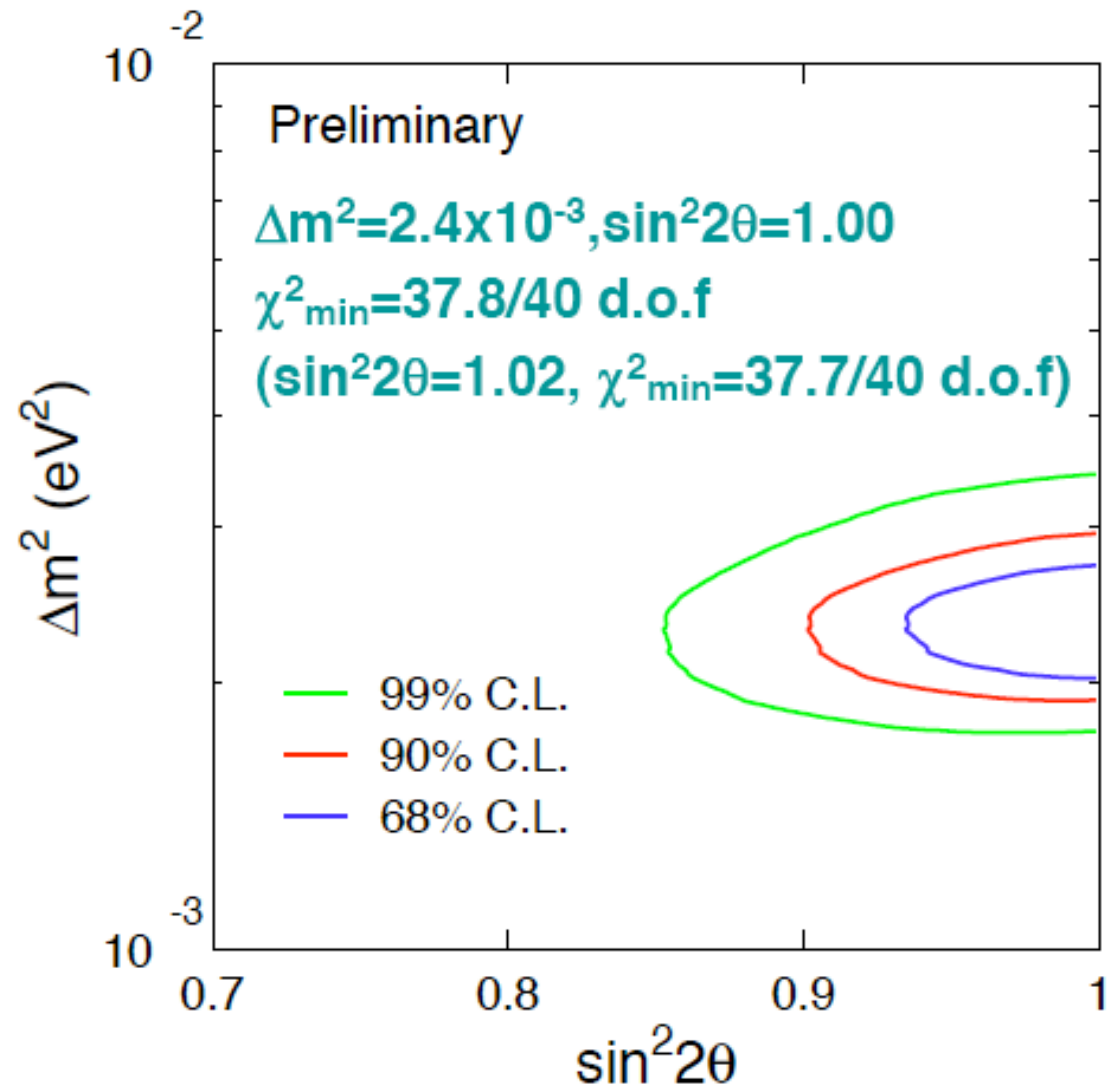
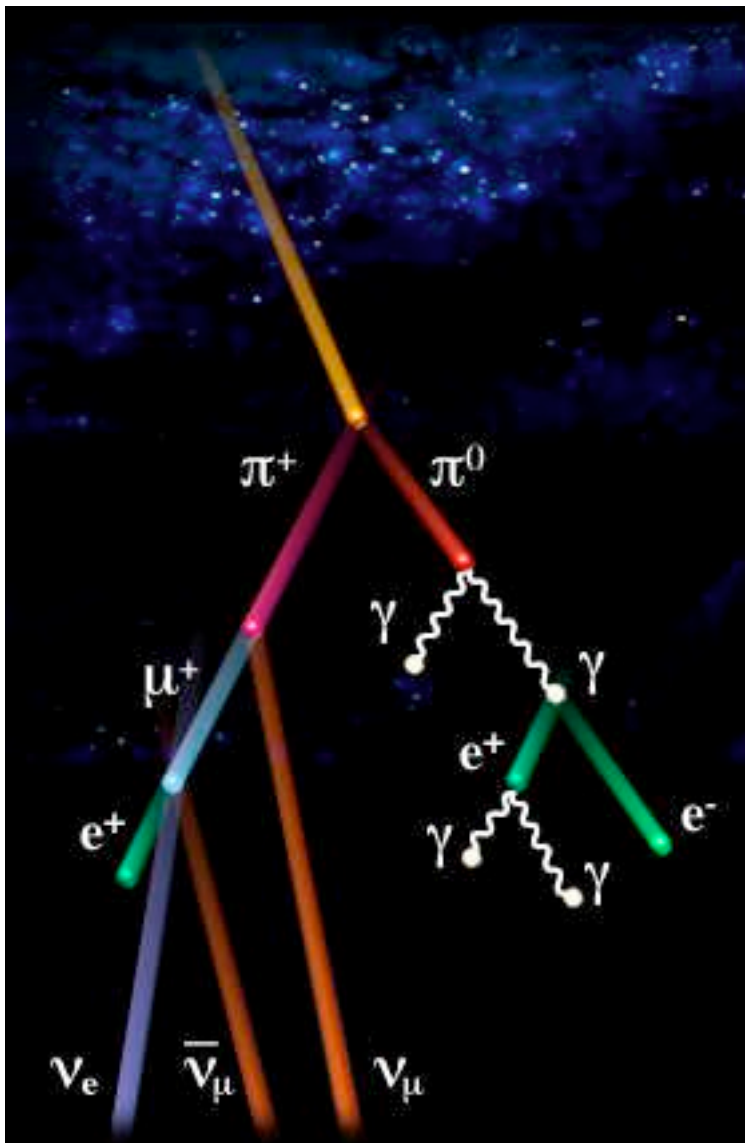


Muon neutrinos disappear from below

Evidence for neutrino oscillations from SuperK



# SuperK result

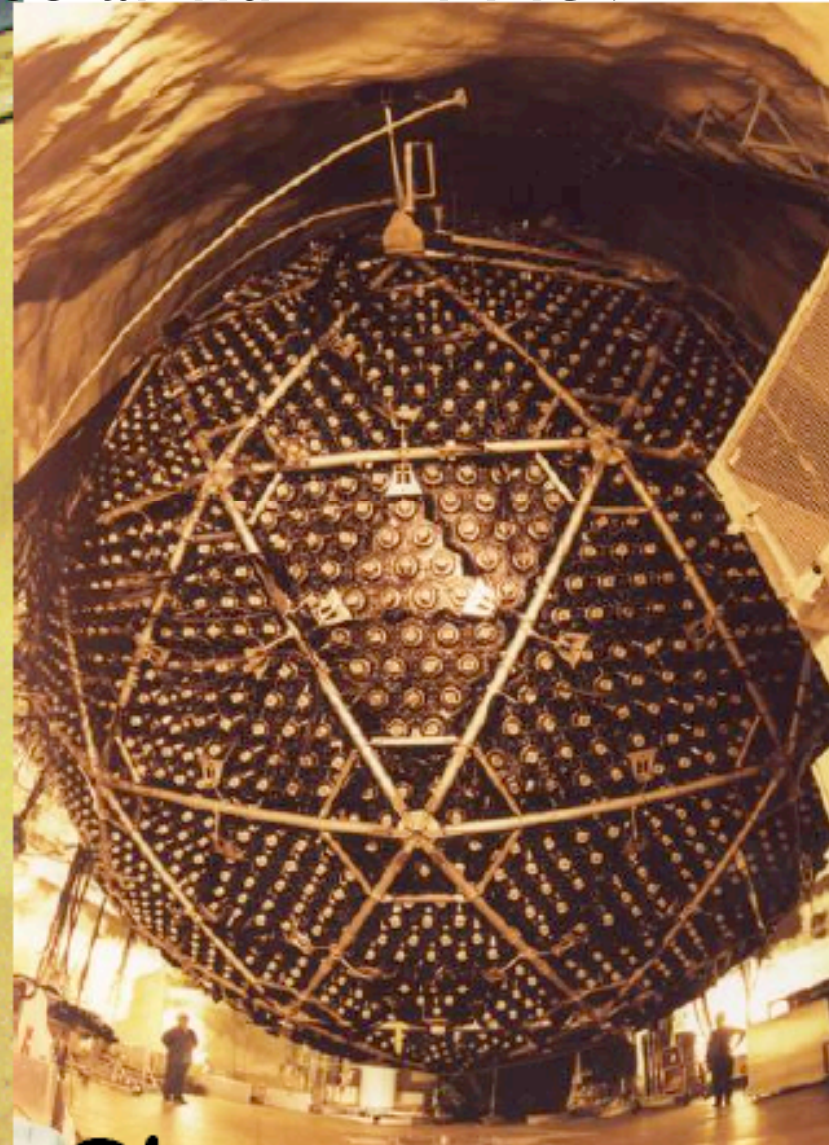




Located in a deep mine ~ 6000 mwe  
because solar  $\nu < 14 \text{ MeV}$

1 kT  
D<sub>2</sub>O  
Heavy Water

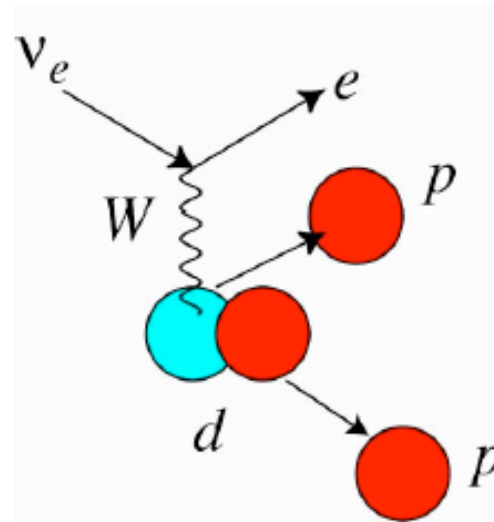
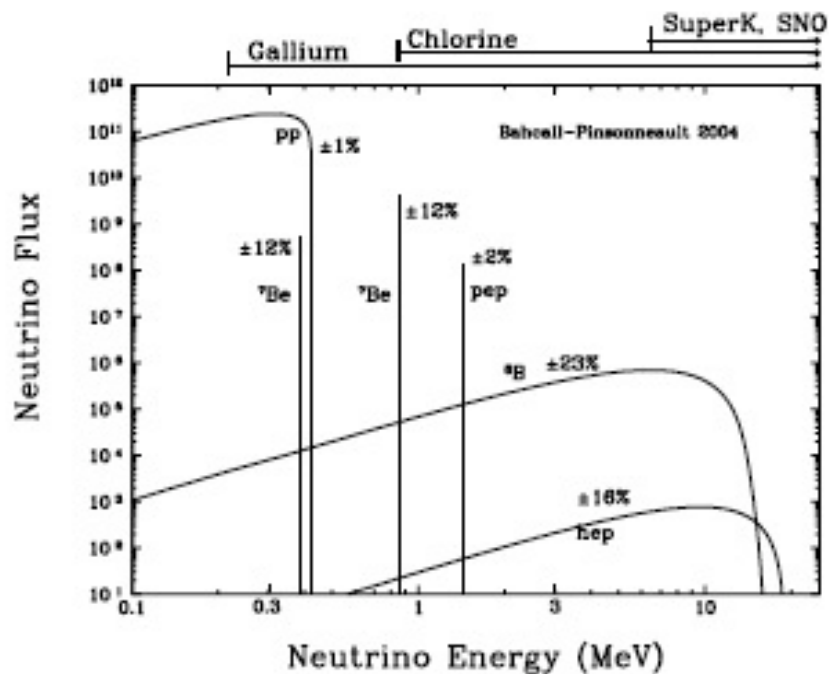
Sudbury Neutrino Observatory



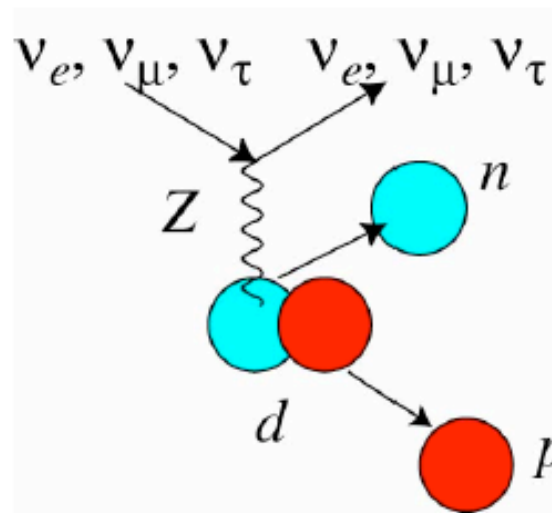


Why does SNO use \$300M worth of heavy water?

The Sun is known to emit electron neutrinos.



**Charged Current**



**Neutral Current**



# Fluxes

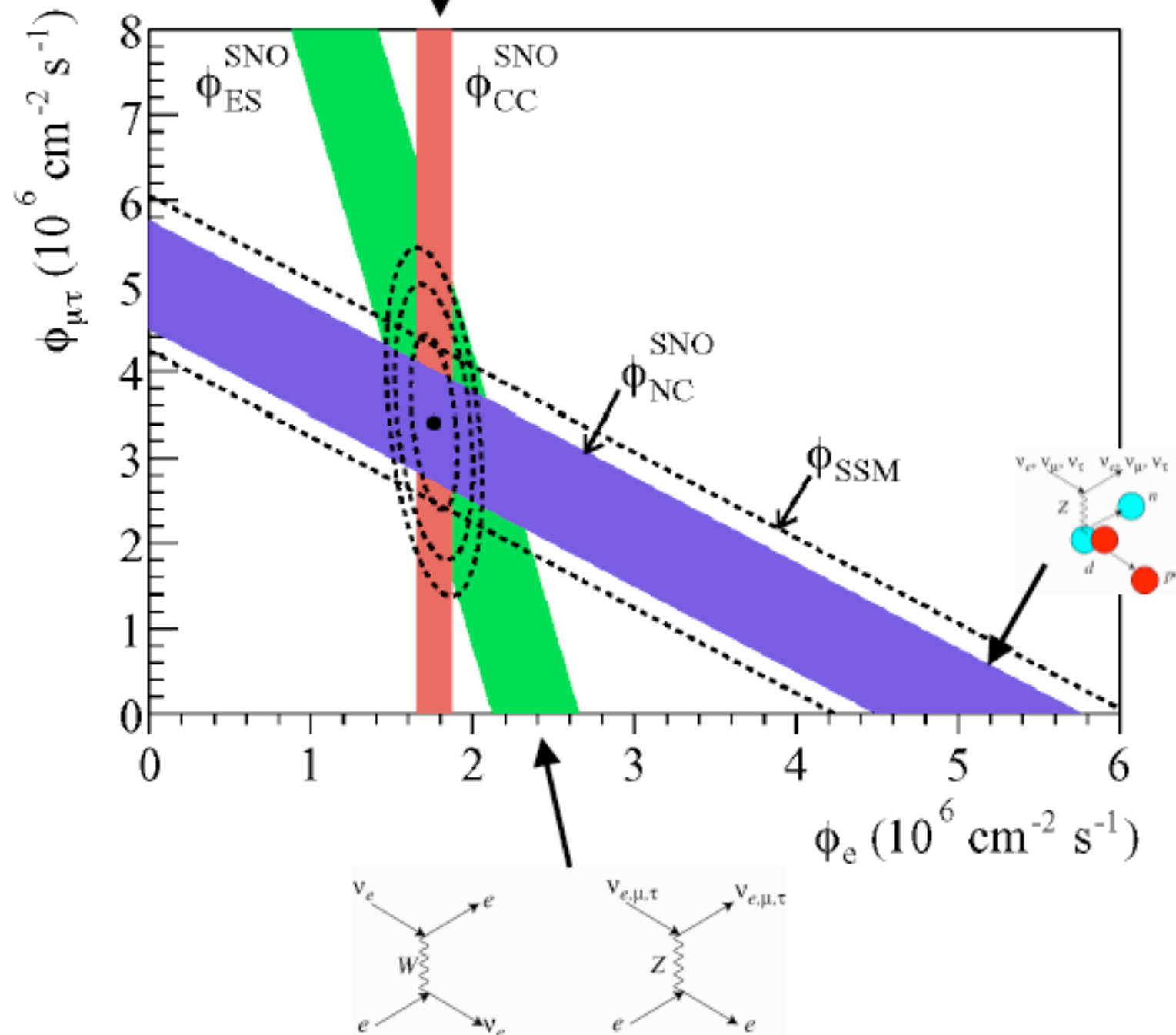
( $10^6 \text{ cm}^{-2} \text{ s}^{-1}$ )

$\nu_e$ : 1.76(11)

$\nu_{\mu\tau}$ : 3.41(66)

$\nu_{\text{total}}$ : 5.09(64)

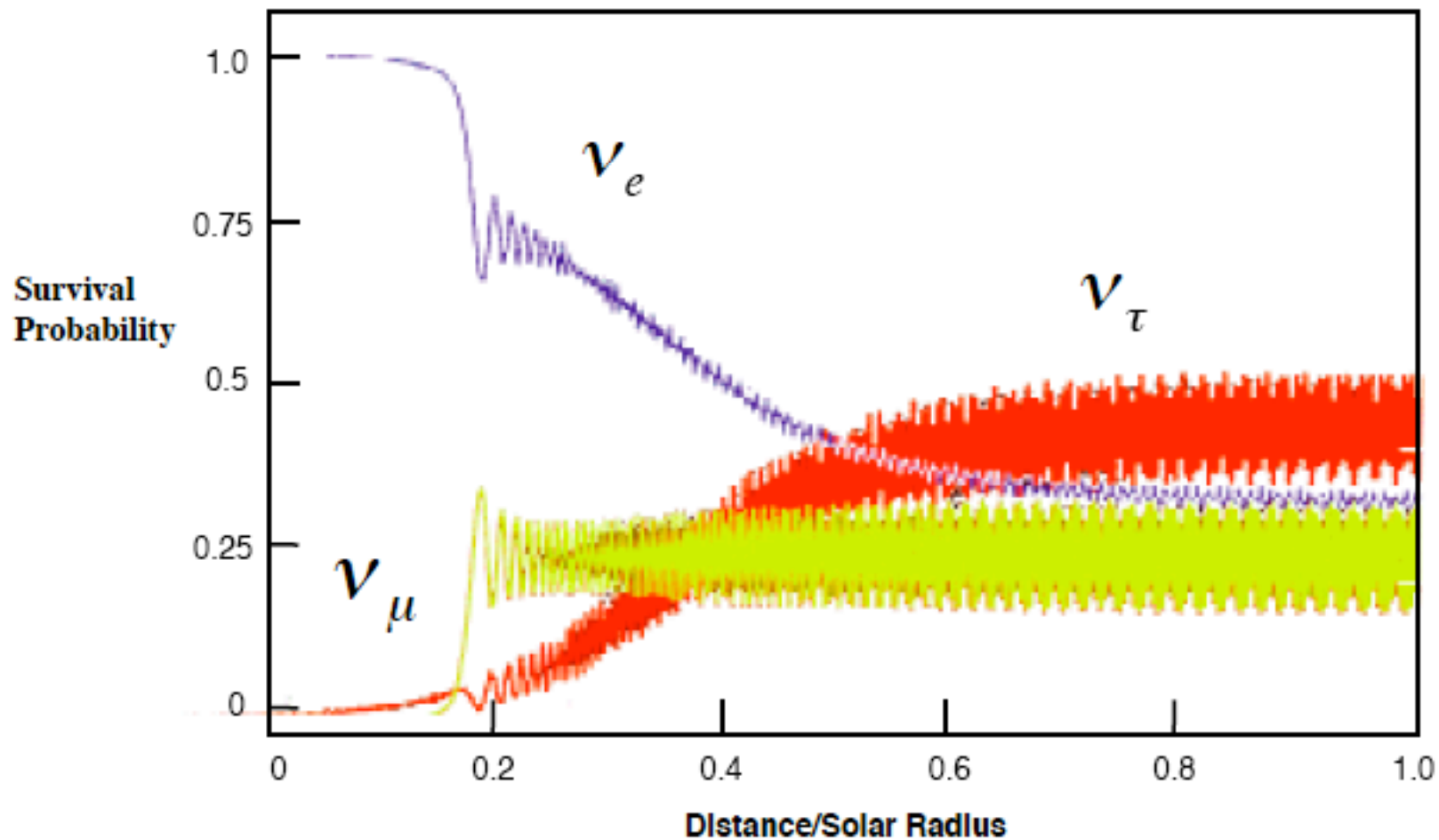
$\nu_{\text{SSM}}$ : 5.05





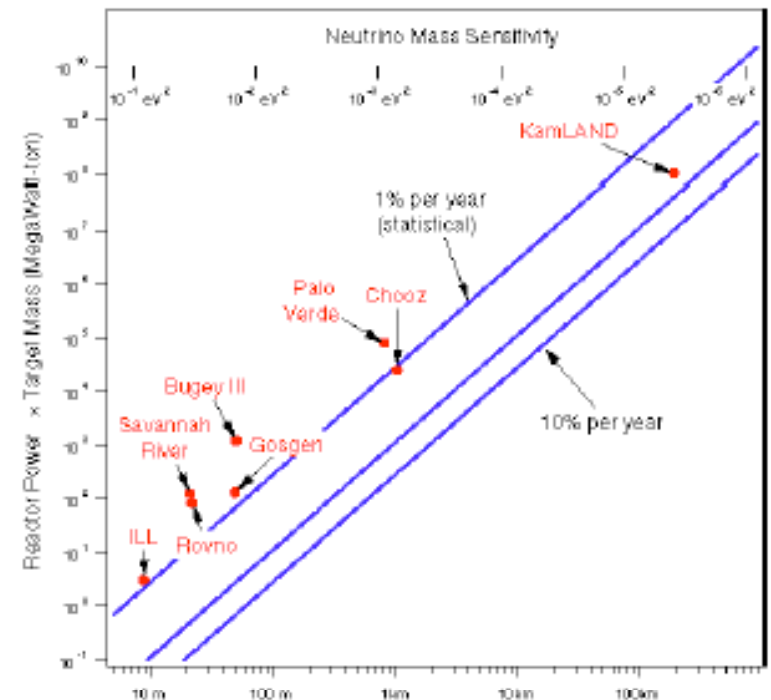
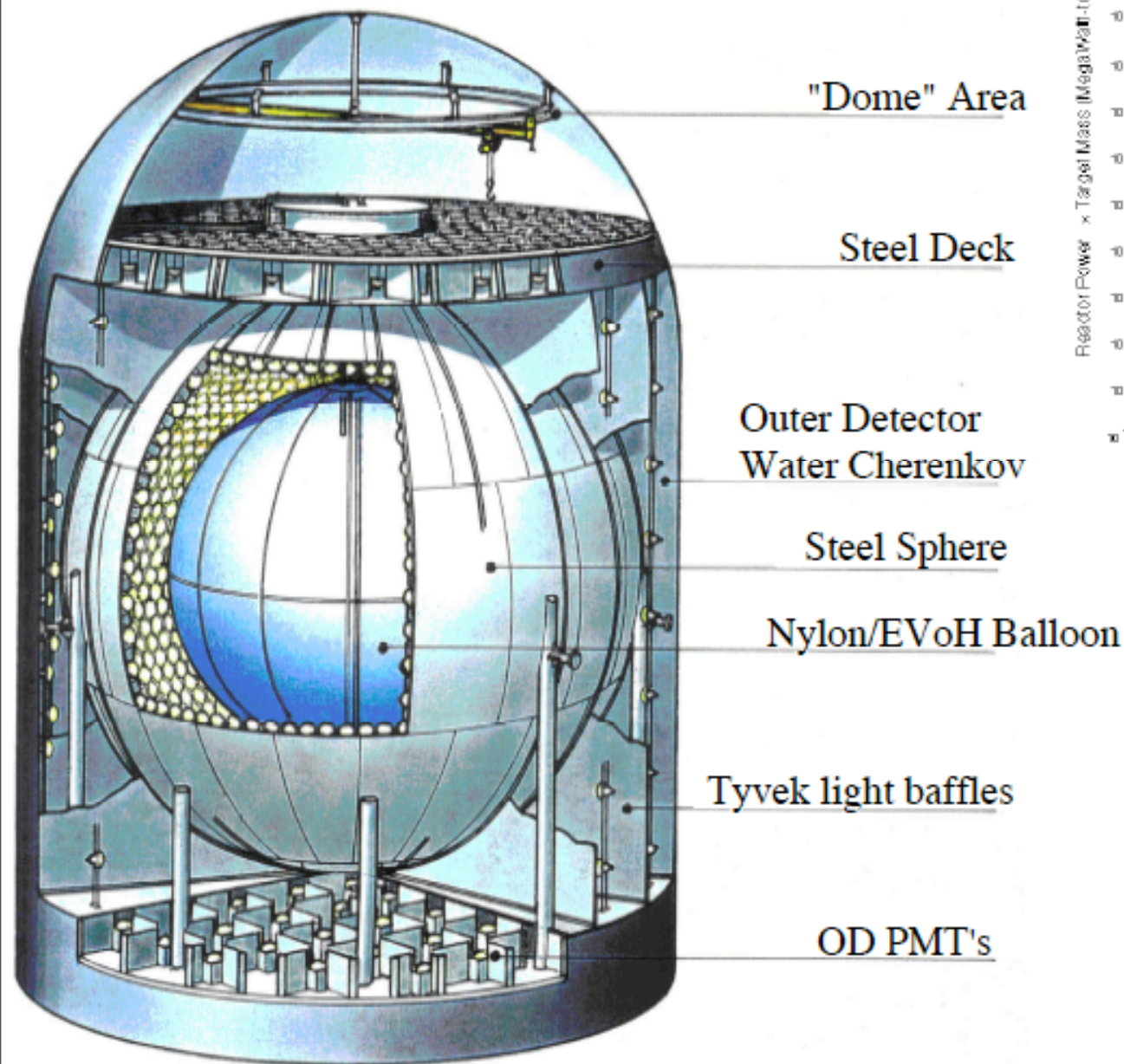
# MSW Effect

$\nu_e$  NC and CC       $\nu_\tau$   $\nu_\mu$  NC only



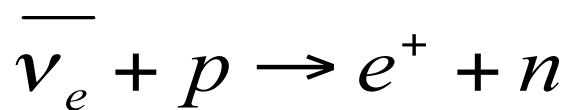


# KamLAND

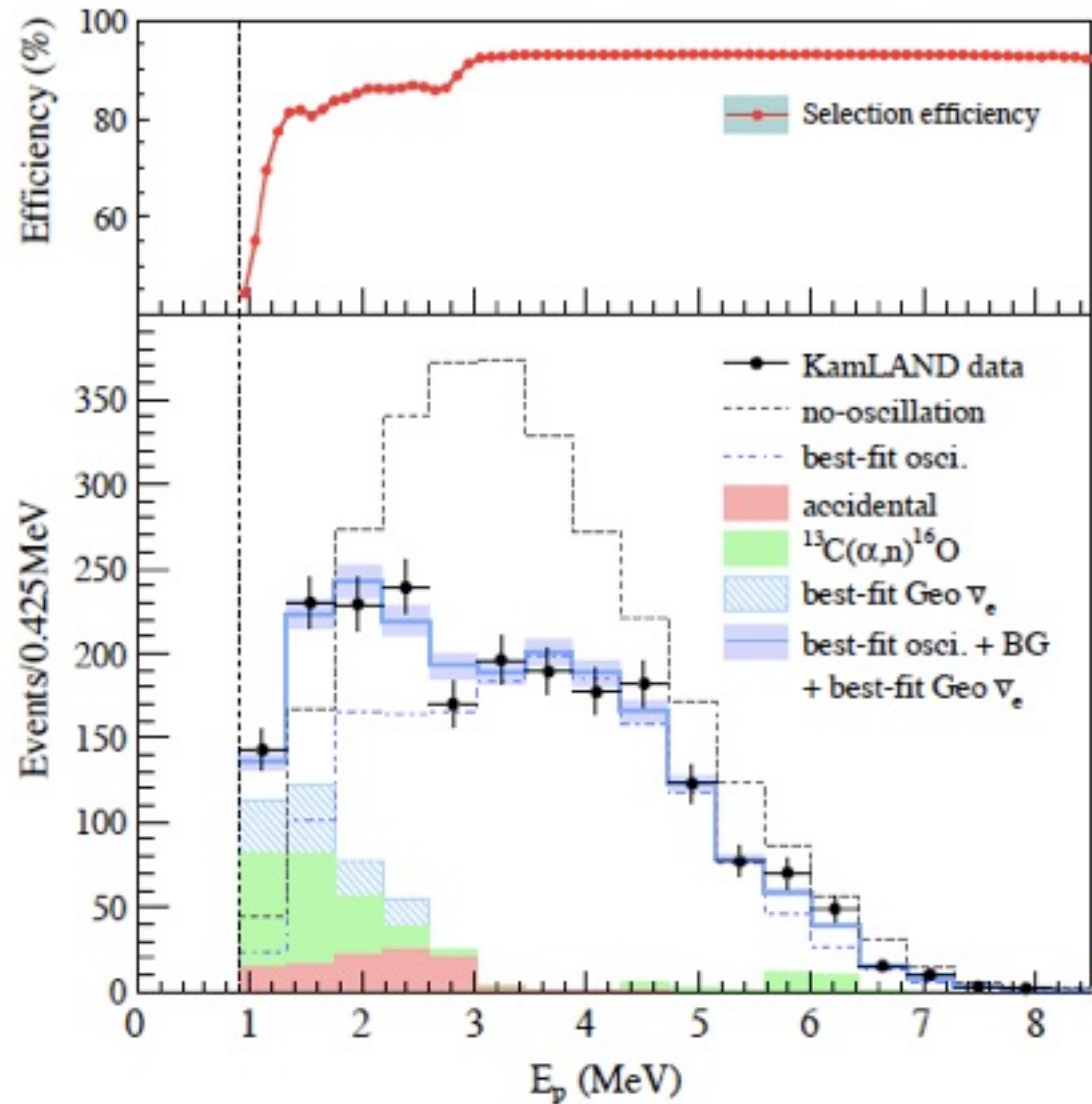




Reactors are  
prolific sources of  
anti-neutrinos  
 $\sim 10^{20}/\text{GW}_{\text{th}}/\text{sec}$

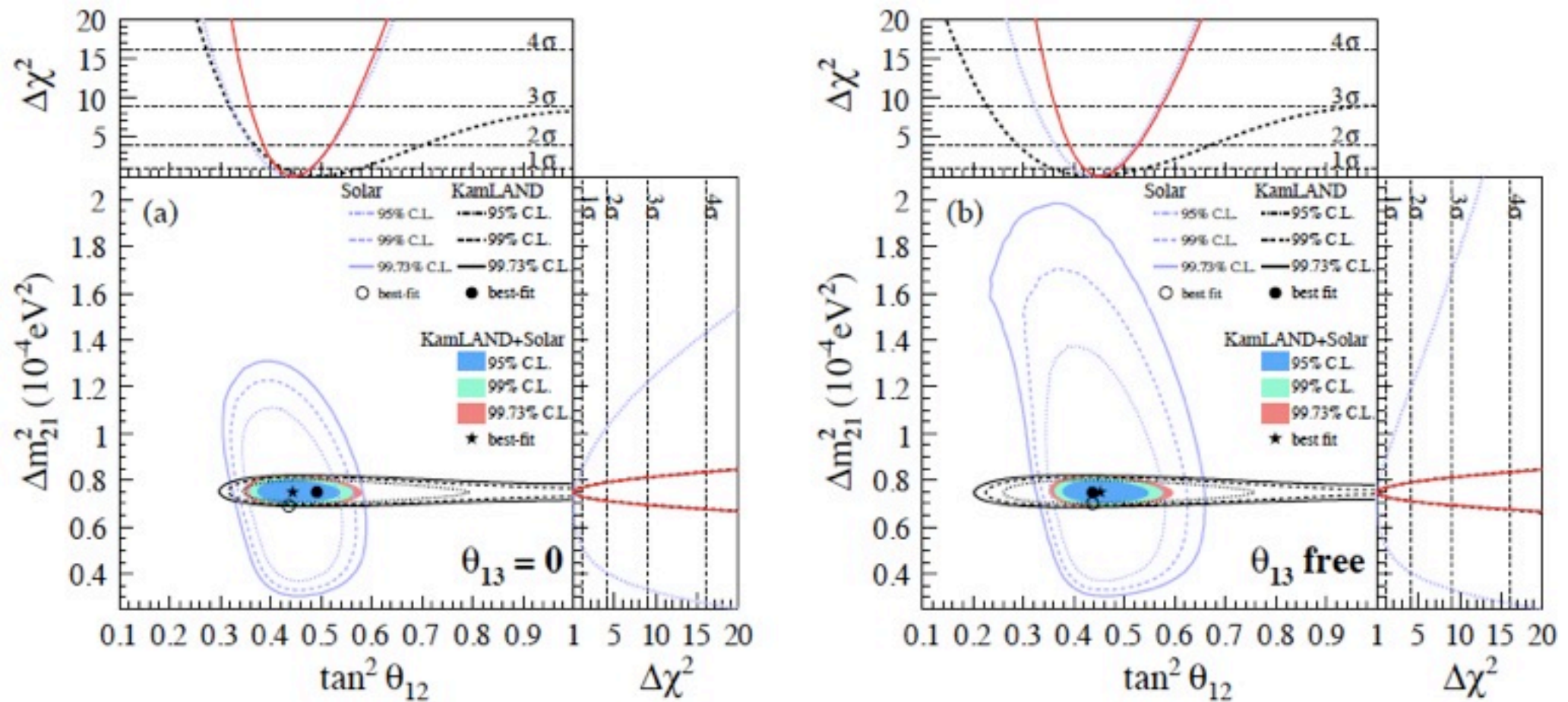


The detection reaction  
is inverse beta decay.  
The final state neutron  
is also detected thru  
absorption on  
hydrogen.



1009:4771





Fit to the entire Solar neutrino and Kamland data

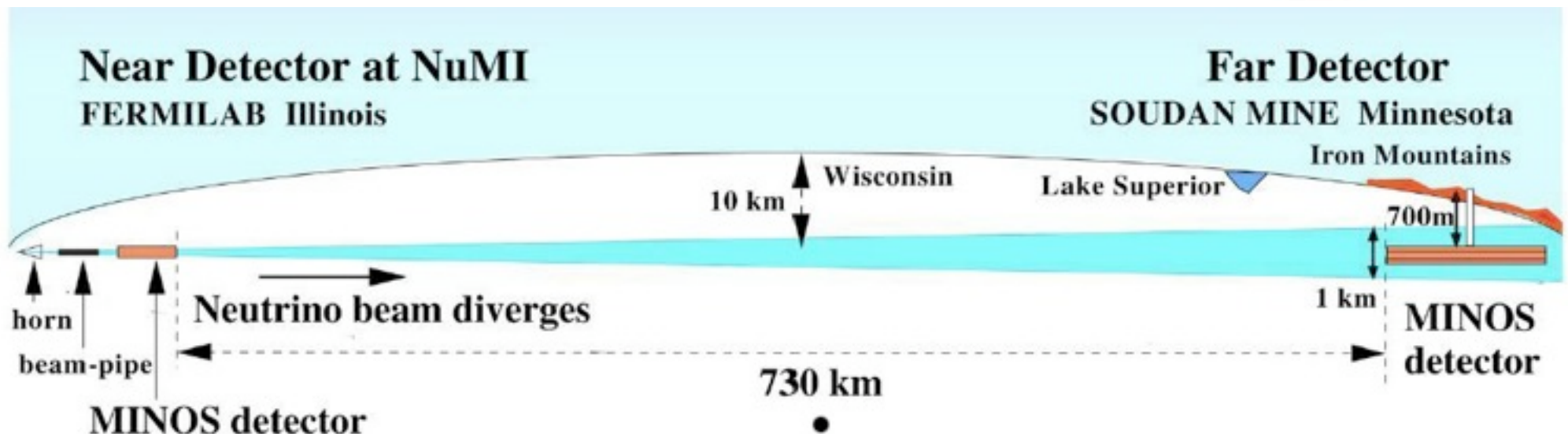


# New Age of Accelerator Neutrinos

- For more precise experiments need pure beams of muon type neutrinos (or anti-neutrinos)
- Better controlled characteristics: energy, spectrum, backgrounds, pulsed.
- High energy ( $>1$  GeV) to provide events with long muons. Better resolution.
- Generally called Long Baseline Experiments.

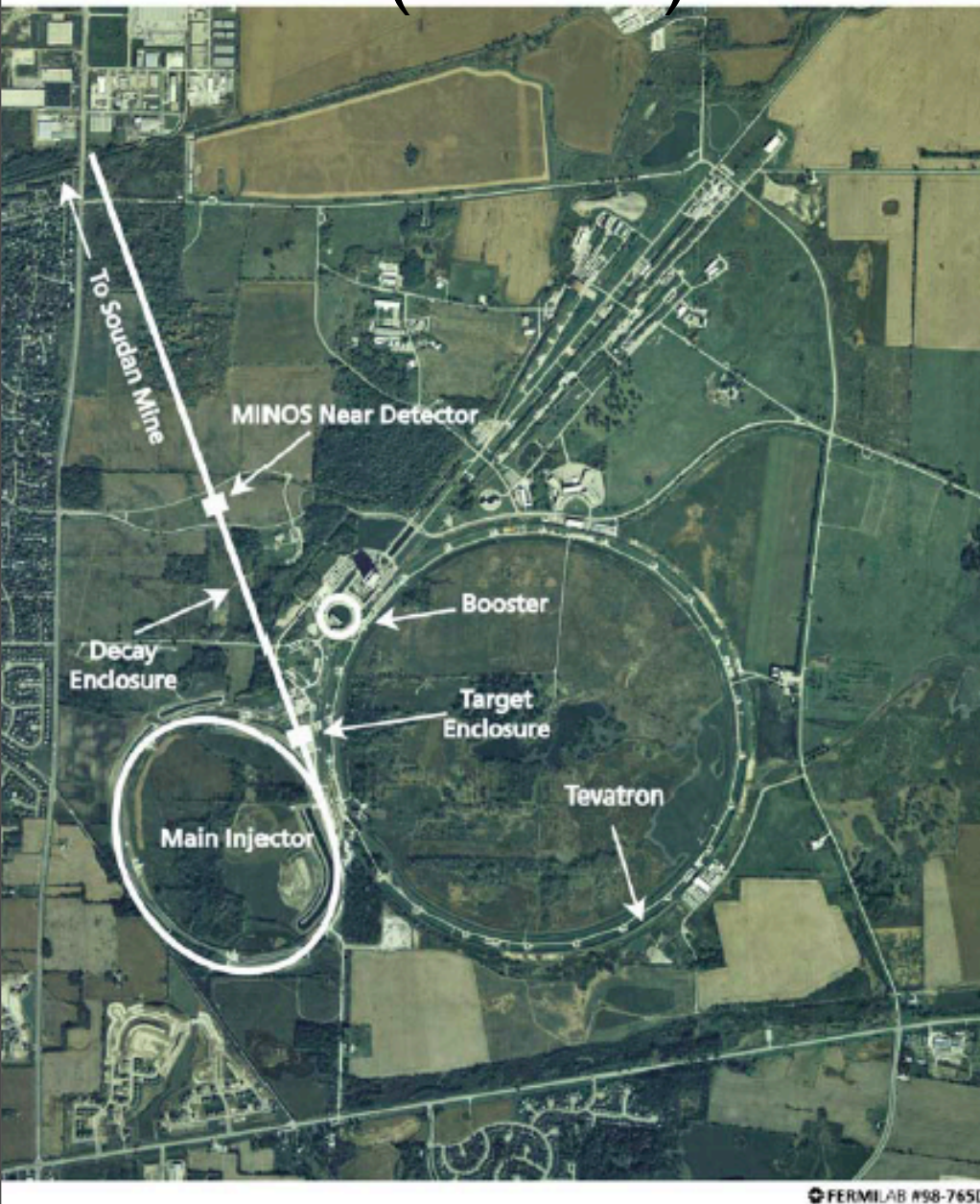


- Prepare a pure beam of muon neutrino beam.
- Aim it towards a large muon detector.
- Observe spectrum of muon neutrinos to see oscillations in energy.



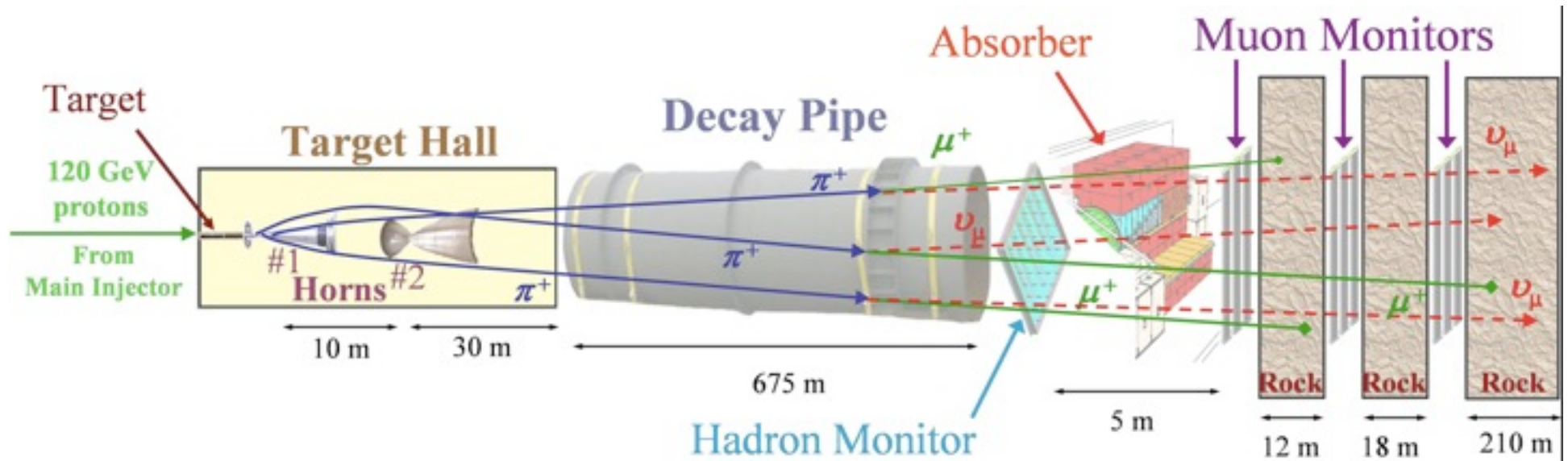


# (Fermilab) Main Injector Neutrino Oscillation (MINOS) about to start running.

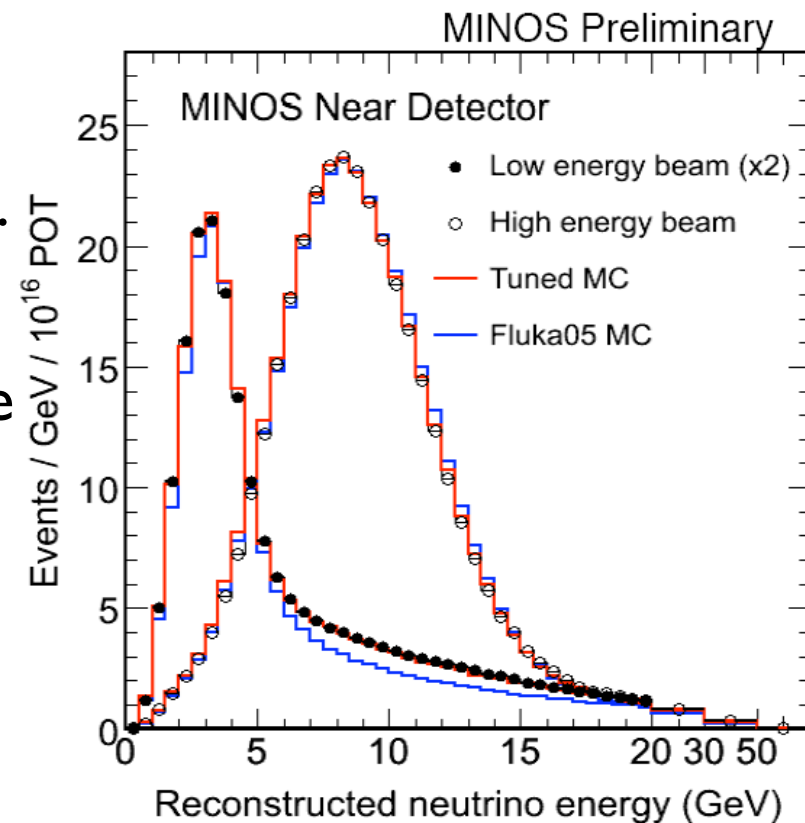


- ★ 120 GeV protons extracted from the MAIN INJECTOR in a single turn ( $8.7\mu\text{s}$ )
- ★ 1.9 s cycle time
- ★ *i.e.*  $\nu$  beam 'on' for  $8.7\mu\text{s}$  every 1.9 s
- ★  $2.5 \times 10^{13}$  protons/pulse
- ★ 0.3 MW on target !
- ★ Initial intensity  
 $2.5 \times 10^{20}$  protons/year



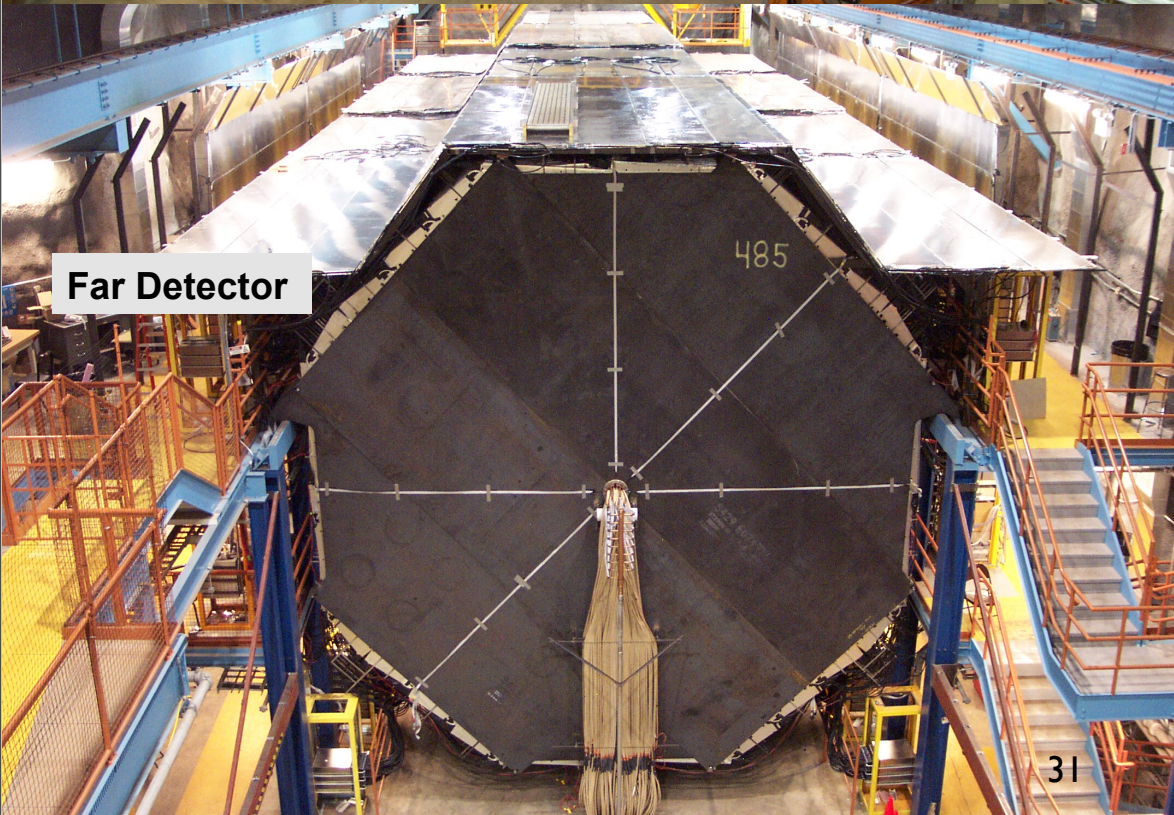


- 120 GeV protons from Main Injector
- Parabolic magnetic horns to sign select pions. Target can be moved to change beam energy.
- 10  $\mu$ sec pulses/2.2 sec,  $3.3 \times 10^{13}$  protons/pulse
- Beam:  $\nu_\mu \sim 91.7\%$ , anti- $\nu_\mu \sim 7\%$ ,  $\nu_e \sim 1.3\%$
- $\nu_\mu$  and anti- $\nu_\mu$  measured.  $\nu_e$  constrained to  $\sim 10\%$  with tuned Monte Carlo.





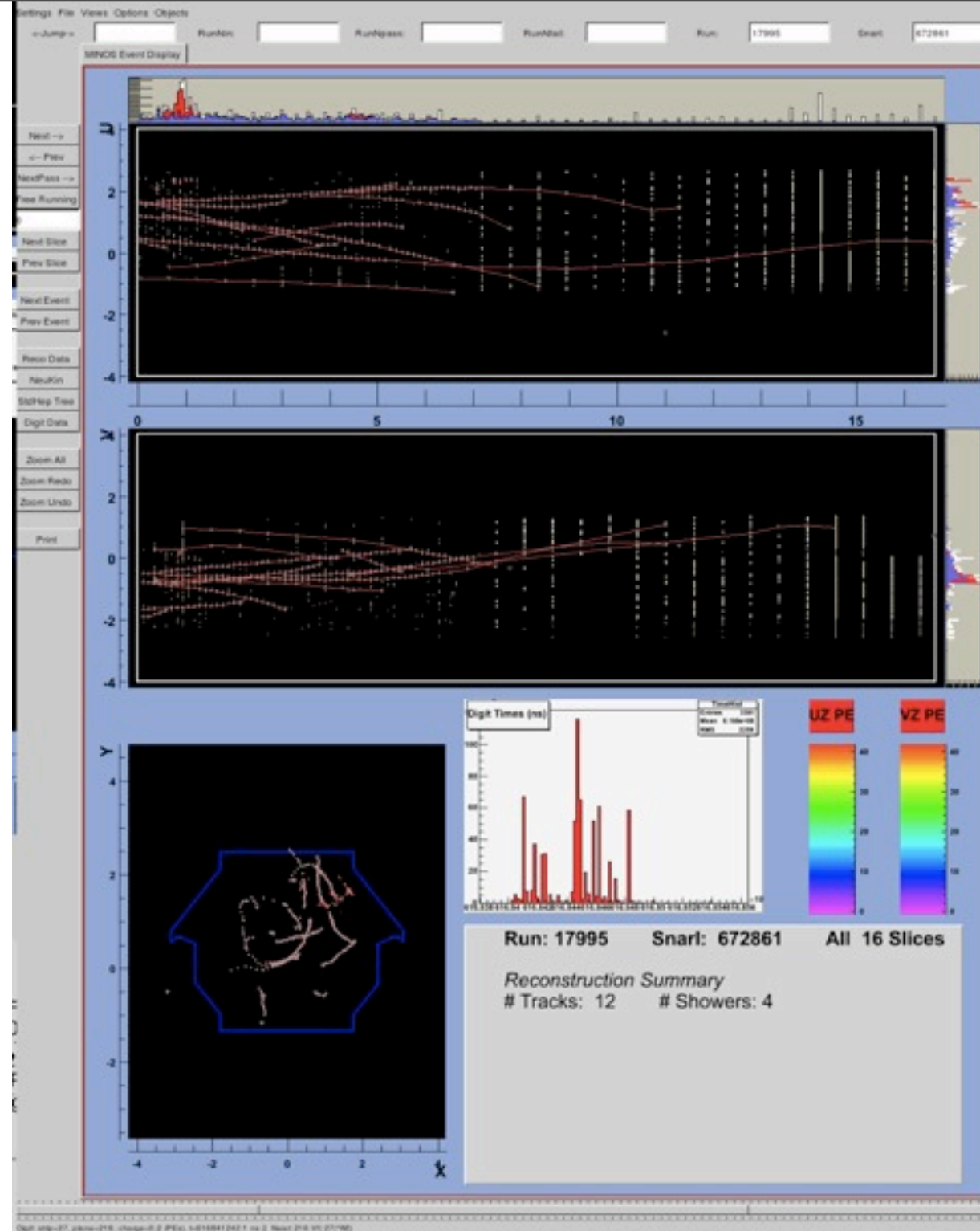
# MINOS Detectors



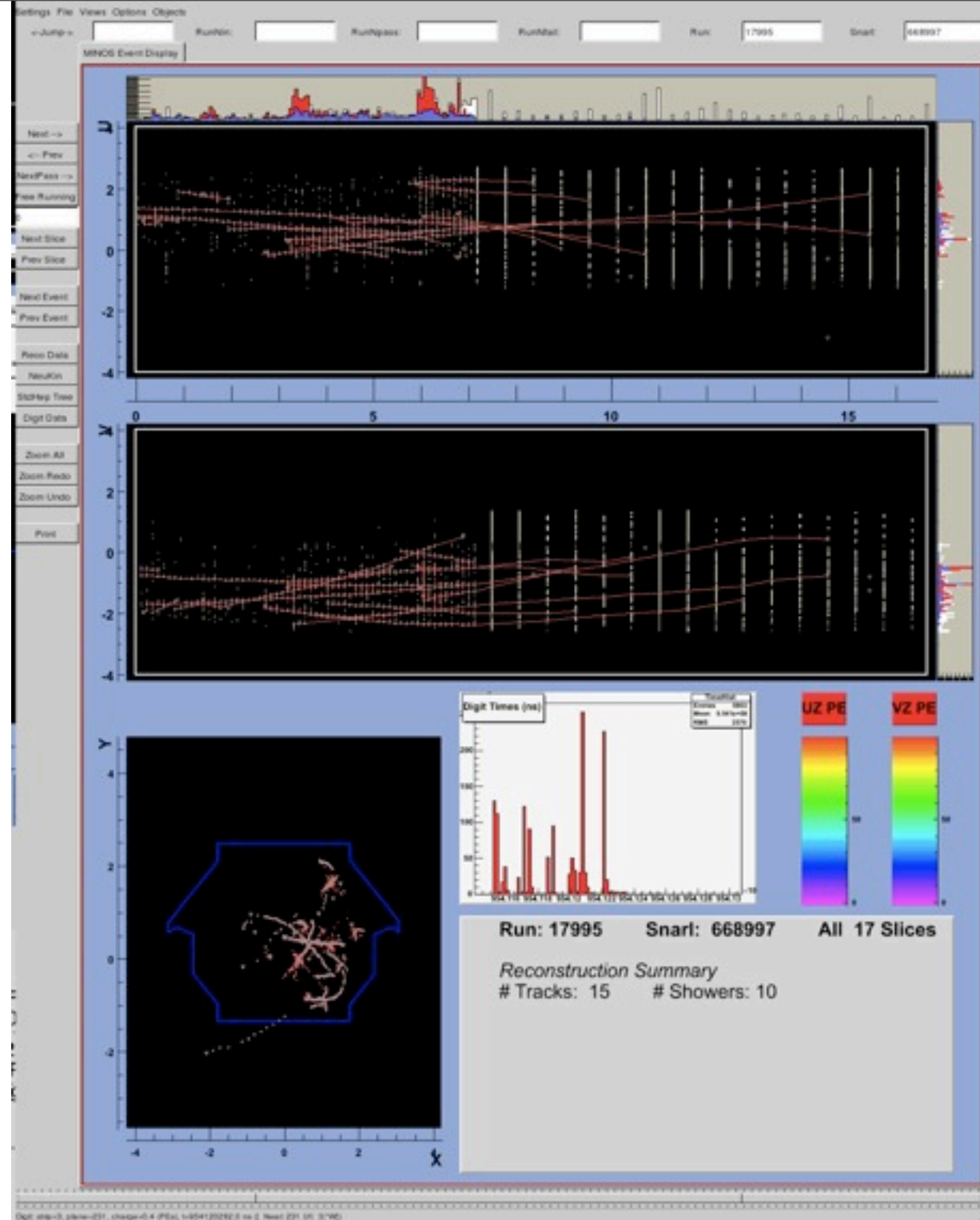
- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon  $\sim$  27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius  $\sim$  3.7 cm
- Wavelength shifting fibre optic readout
- Multi-anode PMTs
- Magnetised ( $\sim$  1.3 T)



# MINOS near detector events

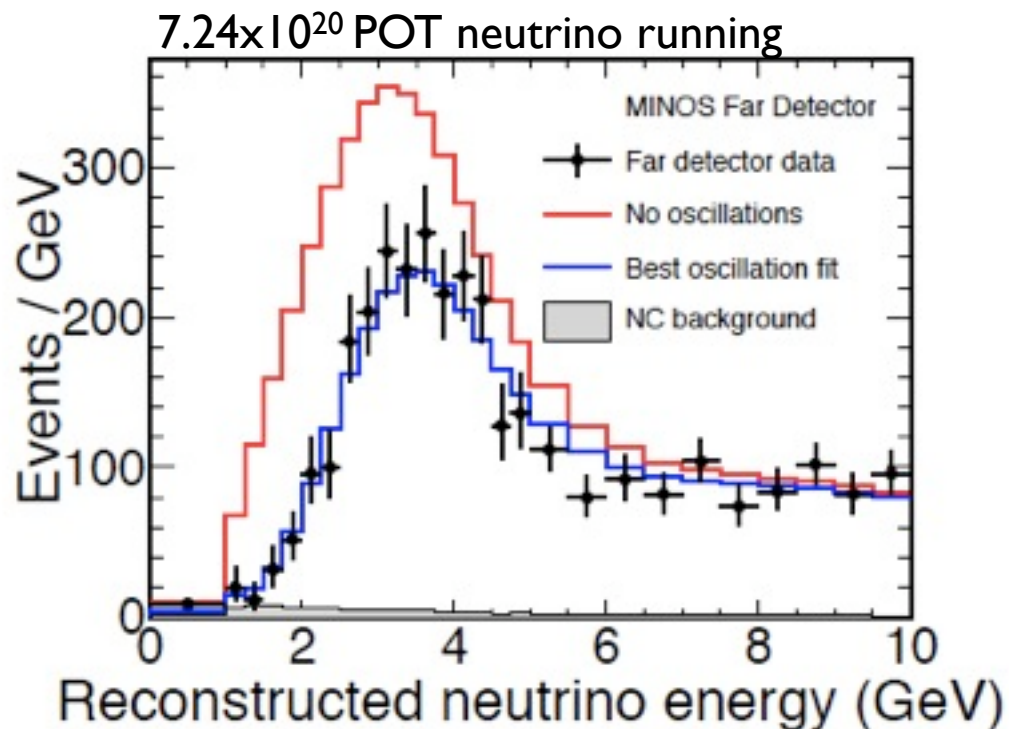




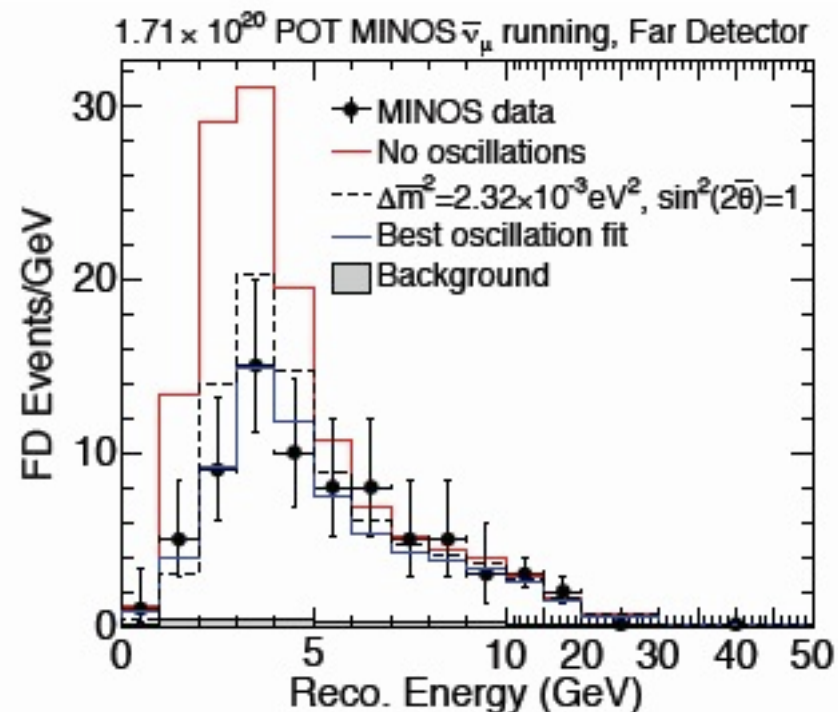




# MINOS data



Expect: 2451  
Observe: 1986



Expect: 156  
Observe: 97

Newest update from last week



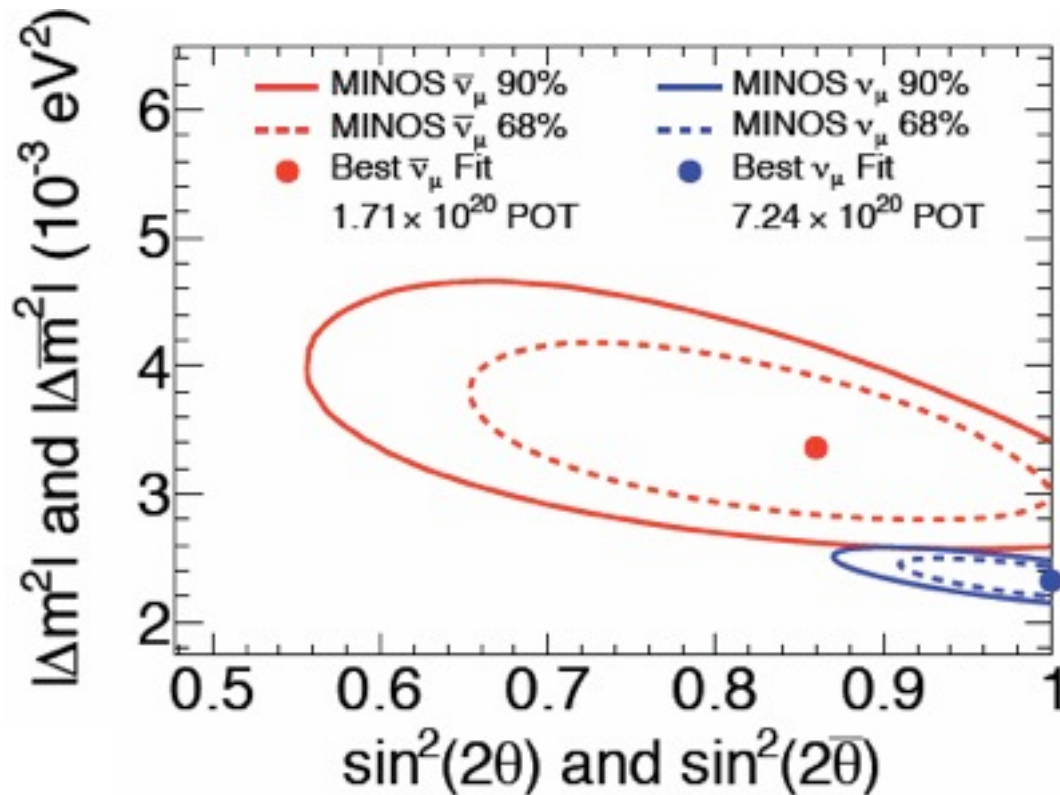
# Neutrinos and Antineutrinos

$$|\Delta \bar{m}_{\text{atm}}^2| = 3.36^{+0.46}_{-0.40} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.86^{+0.11}_{-0.12}$$

$$|\Delta m_{\text{atm}}^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta_{23}) > 0.90 \text{ (90\% C.L.)}$$



Probability that parameters are identical is 2%

More data is being taken



# The Mixing Matrix

$$U = \begin{matrix} \text{Atmospheric} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Cross-Mixing} \\ \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Solar} \\ \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix}$$

$$\begin{matrix} c_{ij} \equiv \cos \theta_{ij} \\ s_{ij} \equiv \sin \theta_{ij} \end{matrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\theta_{12} \approx \theta_{\text{sol}} \approx 34^\circ, \quad \theta_{23} \approx \theta_{\text{atm}} \approx 37\text{-}53^\circ, \quad \theta_{13} \lesssim 10^\circ$$

Majorana ~~CP~~  
phases

$\delta$  would lead to  $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$ . ~~CP~~

Since there are 3 neutrinos, there must be a 3X3 matrix with 3 angles and 1 phase (observable) and 2  $\Delta m^2$



# One Global Fit:

Dominated by

parameter	best fit	$2\sigma$	$3\sigma$
$\Delta m_{21}^2$ [ $10^{-5}\text{eV}^2$ ]	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$ \Delta m_{31}^2 $ [ $10^{-3}\text{eV}^2$ ]	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2 \theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2 \theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2 \theta_{13}$	$0.01^{+0.016}_{-0.011}$	$\leq 0.040$	$\leq 0.056$

KamLAND  
MINOS  
SNO  
SuperK  
Chooz

**arXiv:0808.2016**

Schwetz, Tortola, Valle

Not yet updated for newest results.



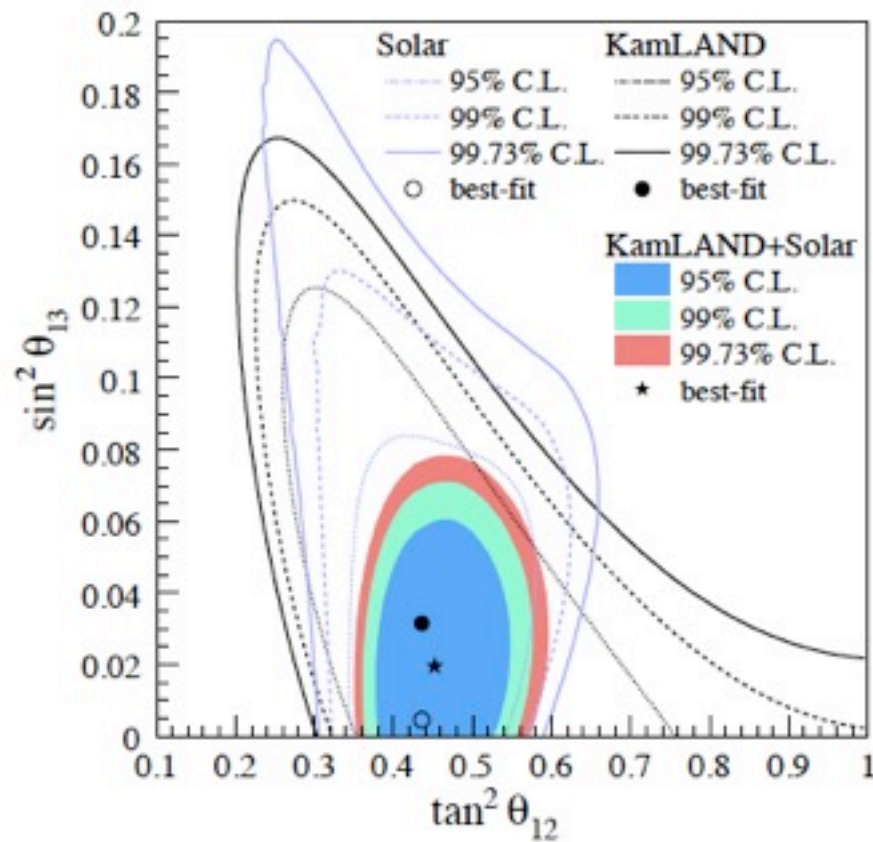


FIG. 3: Allowed regions from the solar and KamLAND data projected in the  $(\tan^2 \theta_{12}, \sin^2 \theta_{13})$  plane for the three-flavor analysis.

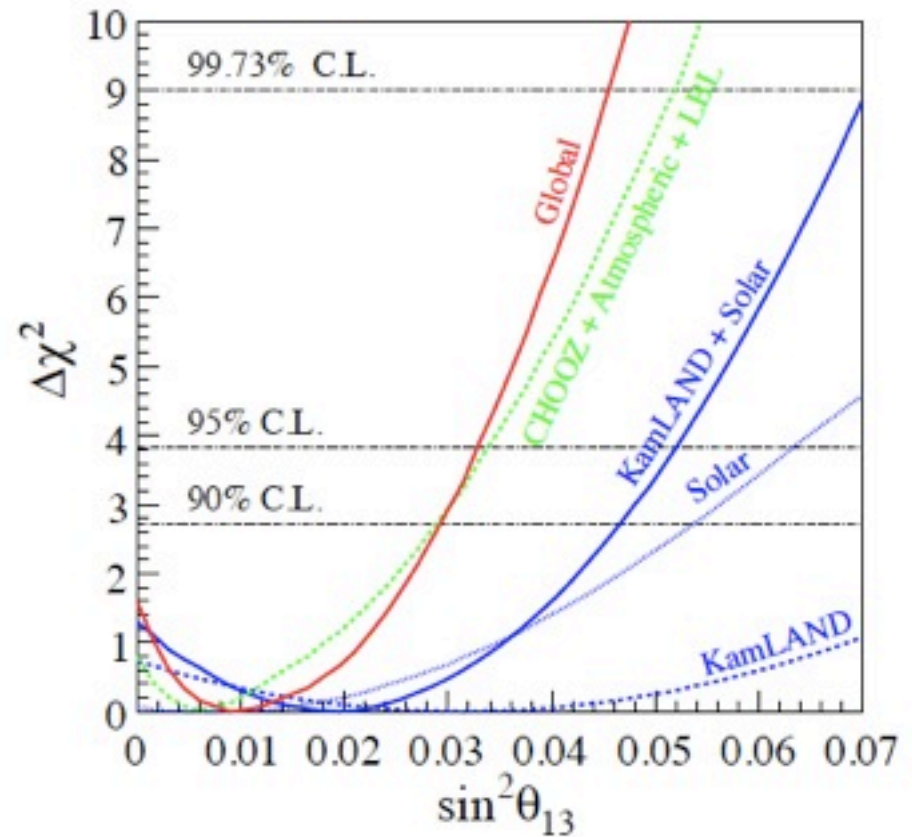


FIG. 4:  $\Delta\chi^2$ -profiles projected onto the  $\sin^2 \theta_{13}$  axis for different combinations of the oscillation data floating the undisplayed parameters  $(\tan^2 \theta_{12}, \Delta m_{21}^2)$ .

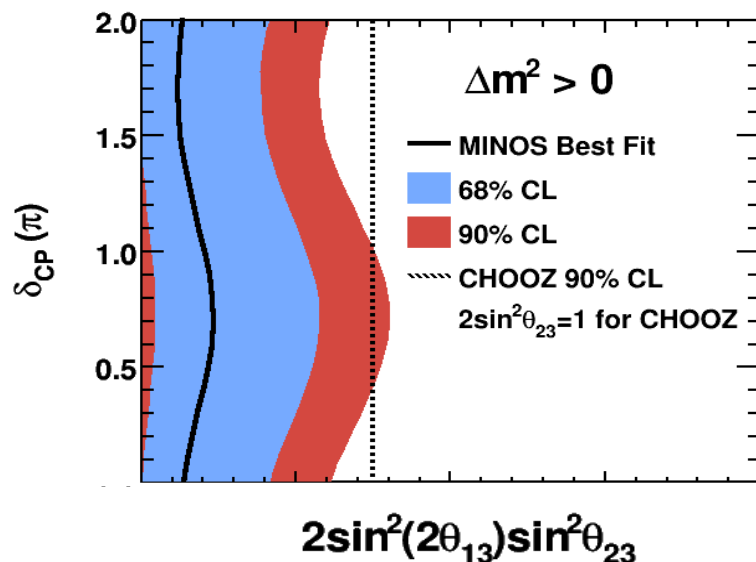
- Solar and Reactor data has weak evidence for the last mixing angle:  $\theta_{13}$



# $\theta_{13}$ Updates



$3.23 \times 10^{19}$  POT  
 1  $\nu_e$  observed  
 8  $\nu_\mu$  observed  
 have 4x data  
 Earthquake will  
 cause delays



MINOS

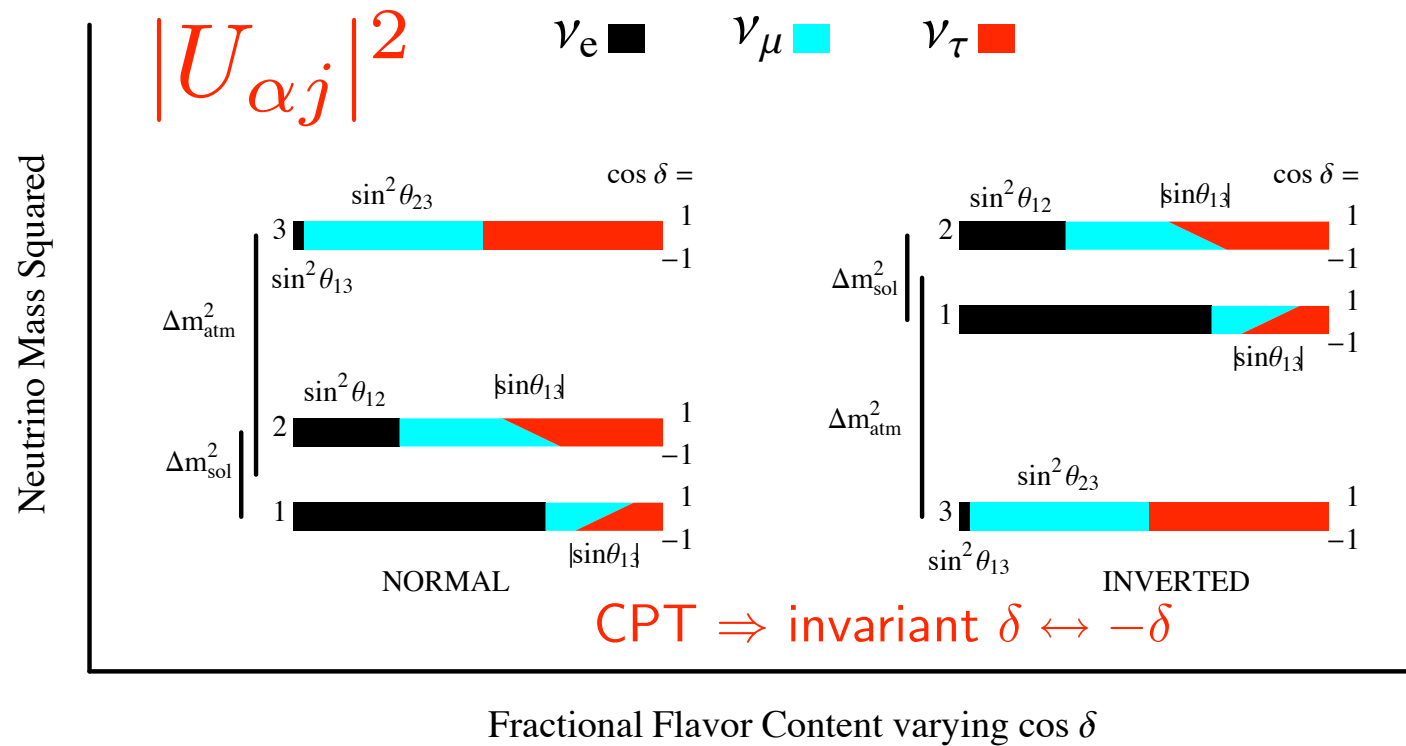
New analysis  
 is on way

for  $\delta_{CP} = 0$ ,  $\sin^2(2\theta_{23}) = 1$ ,

$$|\Delta m_{32}^2| = 2.43 \times 10^{-3} \text{ eV}^2$$

$\sin^2(2\theta_{13}) < 0.12$  normal hierarchy  
 $\sin^2(2\theta_{13}) < 0.20$  inverted hierarchy  
 at 90% C.L.





$$\delta m_{\text{sol}}^2 = +7.6 \times 10^{-5} \text{ eV}^2$$

$$|\delta m_{\text{atm}}^2| = 2.4 \times 10^{-3} \text{ eV}^2$$

$$|\delta m_{\text{sol}}^2| / |\delta m_{\text{atm}}^2| \approx 0.03$$

$$\sin^2 \theta_{12} \sim 1/3$$

$$\sin^2 \theta_{23} \sim 1/2$$

$$\sin^2 \theta_{13} < 3\%$$

$$\sqrt{\delta m_{\text{atm}}^2} = 0.05 \text{ eV} < \sum m_{\nu_i} < 0.5 \text{ eV} = 10^{-6} * m_e$$

$$0 \leq \delta < 2\pi$$

parke



# Long Range Interactions

- Diversion to illustrate the power of interferometry using the MINOS  $\nu$ - $\bar{\nu}$  discrepancy.
- What could distinguish  $\nu$  and  $\bar{\nu}$  ?
- A new charge and very feeble interaction that distinguishes flavor ?
- Davoudiasl, Lee, Marciano. Other work: Joshipura, Mohanty(2003), others...



- An ultra-light  $z'$  boson and very feeble interaction.
- Must work over astronomical scales.
- Postulate a charge:  $Q = (B-L) + (L_\mu - L_\tau)$

	e-	Proton	Neutron	$\nu_\mu$	$\nu_\tau$
Q	-1	1	1	0	-2

Potential due to neutrons in the Sun and Earth

Put  $M_z = 10^{-18} \text{ eV}$ ,

$$V_n = \alpha' \left( \frac{N_n^\oplus}{R_\oplus} + \frac{N_n^\odot}{R_{\text{ES}}} \right) = 2.24 \times 10^{-12} \text{ eV} \left( \frac{\alpha'}{10^{-50}} \right) \left[ 0.25 + \left( \frac{R_{\text{AU}}}{R_{\text{ES}}} \right) \right]$$

$$N_n^\odot = 1.70 \times 10^{56} \text{ and } N_n^\oplus = 1.78 \times 10^{51}.$$

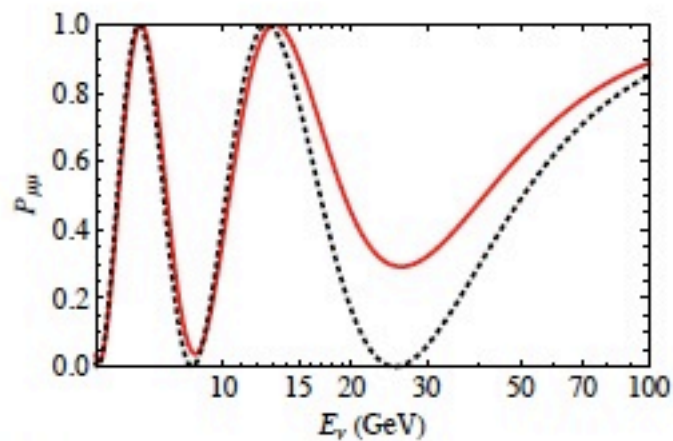
$$R_\oplus = 6.4 \times 10^3 \text{ km}$$

$$R_{\text{ES}}^a \simeq 1.52 \times 10^8 \text{ km, aphelion } (\sim \text{July 4})$$

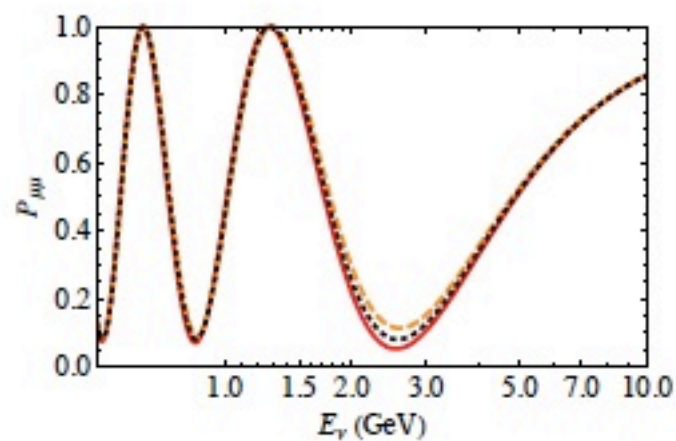
$$R_{\text{ES}}^p \simeq 1.47 \times 10^8 \text{ km, perihelion } (\sim \text{January 4}).$$

Phenomenology is  
same as MSW



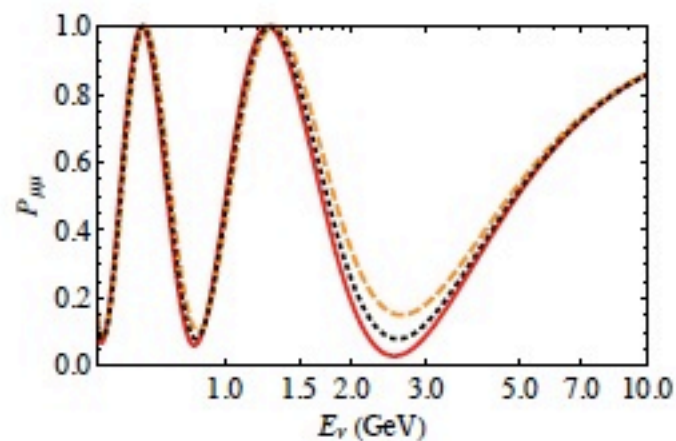
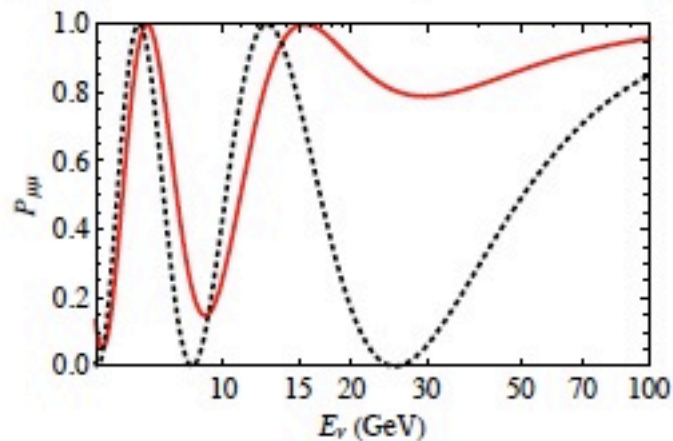


(a)



(b)

Above: SM (black dotted), LRI (red solid) with  $\Delta m_{23}^2 = 2.45 \times 10^{-3} \text{ eV}^2$  and  $\alpha' = 0.5 \times 10^{-52}$ . (a)  $L = 2 \times 6400 \text{ km}$  (DEEP CORE experiment) with  $\sin^2(2\theta_{23}) = 1$ . (b)  $L = 1300 \text{ km}$  (DUSEL) with  $\sin^2(2\theta_{23}) = 0.92$ .  $\nu$ : red solid,  $\bar{\nu}$ : dashed orange. Below:  $\alpha' = 1.0 \times 10^{-52}$

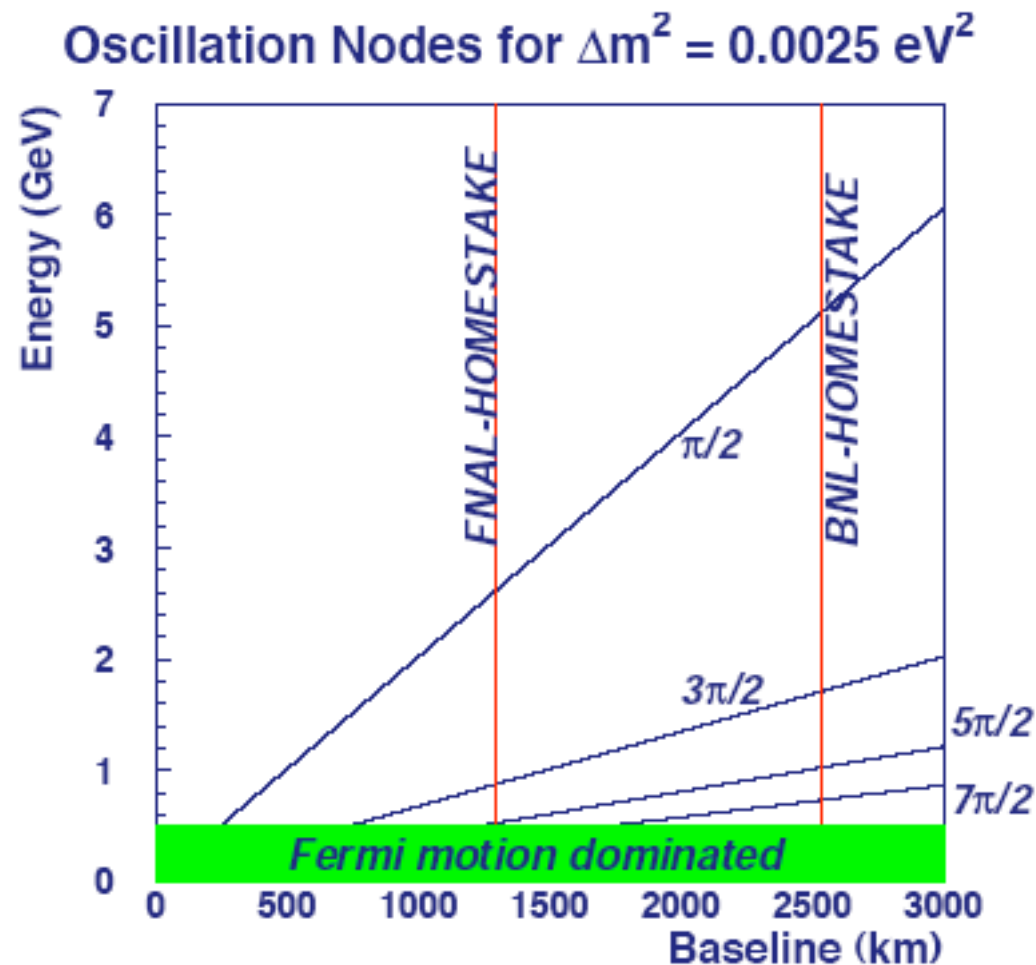


Limit on  $\alpha'$  is already  $< 5 \times 10^{-52}$  from rough fit current MINOS data. Weaker than gravity ! Neutrinos may be the only window on such interactions.



# Must see full consequence of oscillations

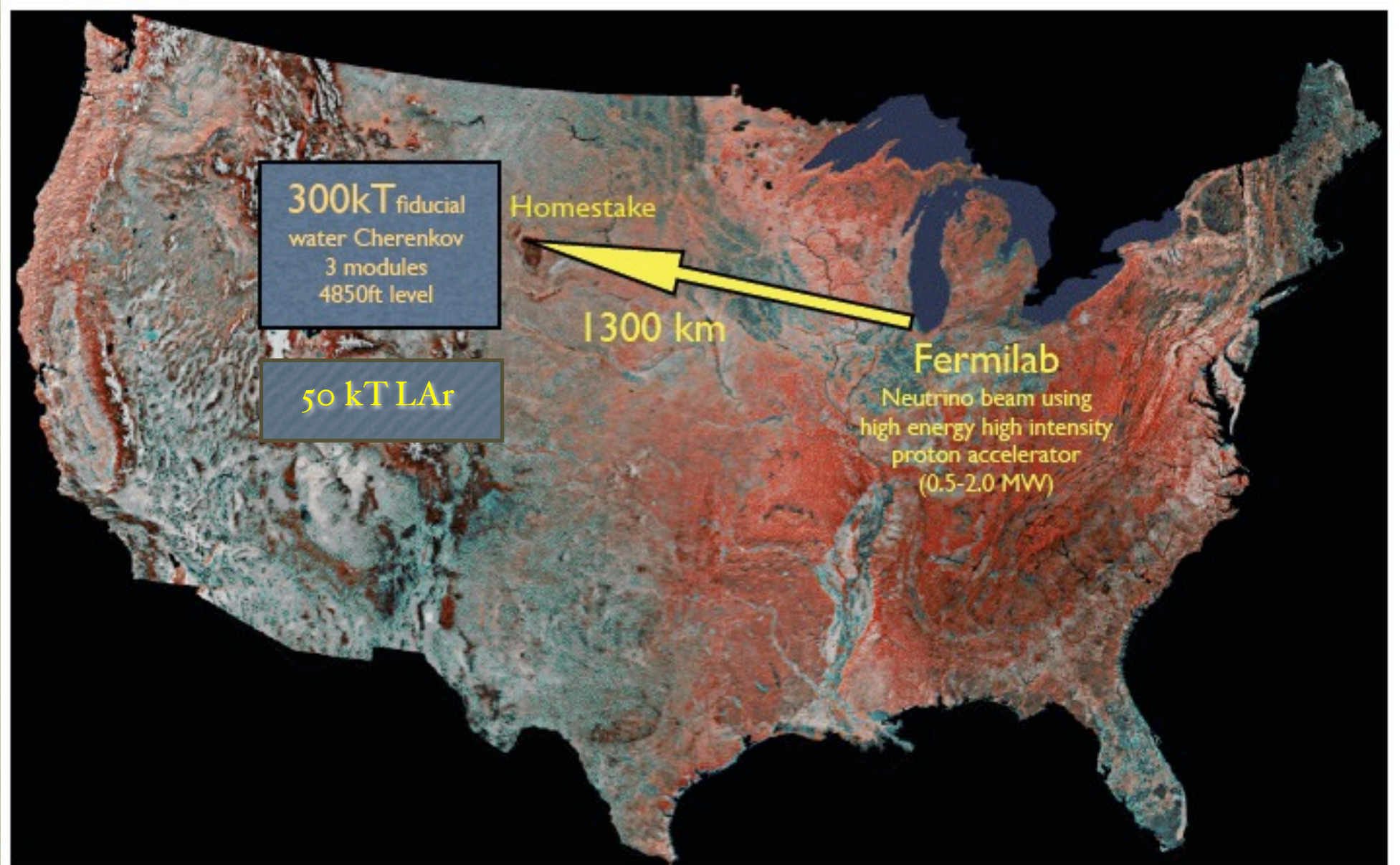
- Must see multiple nodes in a spectrum for precise measurements
- Need E: 1-6 GeV
- Need  $\sim 2000$  km
- Need intense beam.
- Need very large (200kTon) detector to get enough events
- Must place detector underground



(M. Diwan, hep-ex/0407047)



# Long-Baseline Neutrino Experiment





# $\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

matter effect  $\sim E$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta)$$

$\sim 7500$  km  
no CPV.  
magic bln

CPV term  
approximate  
dependence  
 $\sim L/E$

$$+\alpha \frac{8J_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)$$

$$+\alpha \frac{8I_{CP}}{\hat{A}(1 - \hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)$$

$$+\alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

solar term

linear dep.

$$J_{CP} = 1/8 \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2, \Delta = \Delta m_{31}^2 L / 4E$$

$$\hat{A} = 2VE / \Delta m_{31}^2 \approx (E_\nu / \text{GeV}) / 11 \text{ For Earth's crust.}$$

CP asymmetry grows as  
this becomes smaller



# Technology for the new experiment

- An experimental project of this kind needs and affects technical development in many fields.
- Material science: a high intensity/radiation target must be developed.
- Glass/ceramics: Photomultiplier tubes that can withstand ultrapure water at high pressure must be developed.
- Biology: need to keep water clean !
- Understanding cryogenics on a large scale underground
- Underground construction: Deep stable caverns in hard rock. The scales needed are new for engineering.
- Accelerator science: new very high intensity beams.



# The Neutrino Beam Facility at Fermilab

Start with a 700 kW beam, and then take profit of the significantly increased beam power (2.3 MW) available with Project X

- Allow NUMI/MINERVA/NOvA running with LBNE
- Maximize distance between target and Near Detector (now 603 m to upstream end)
- Need a wide band beam to cover 1<sup>st</sup> and 2<sup>nd</sup> osc. maxima

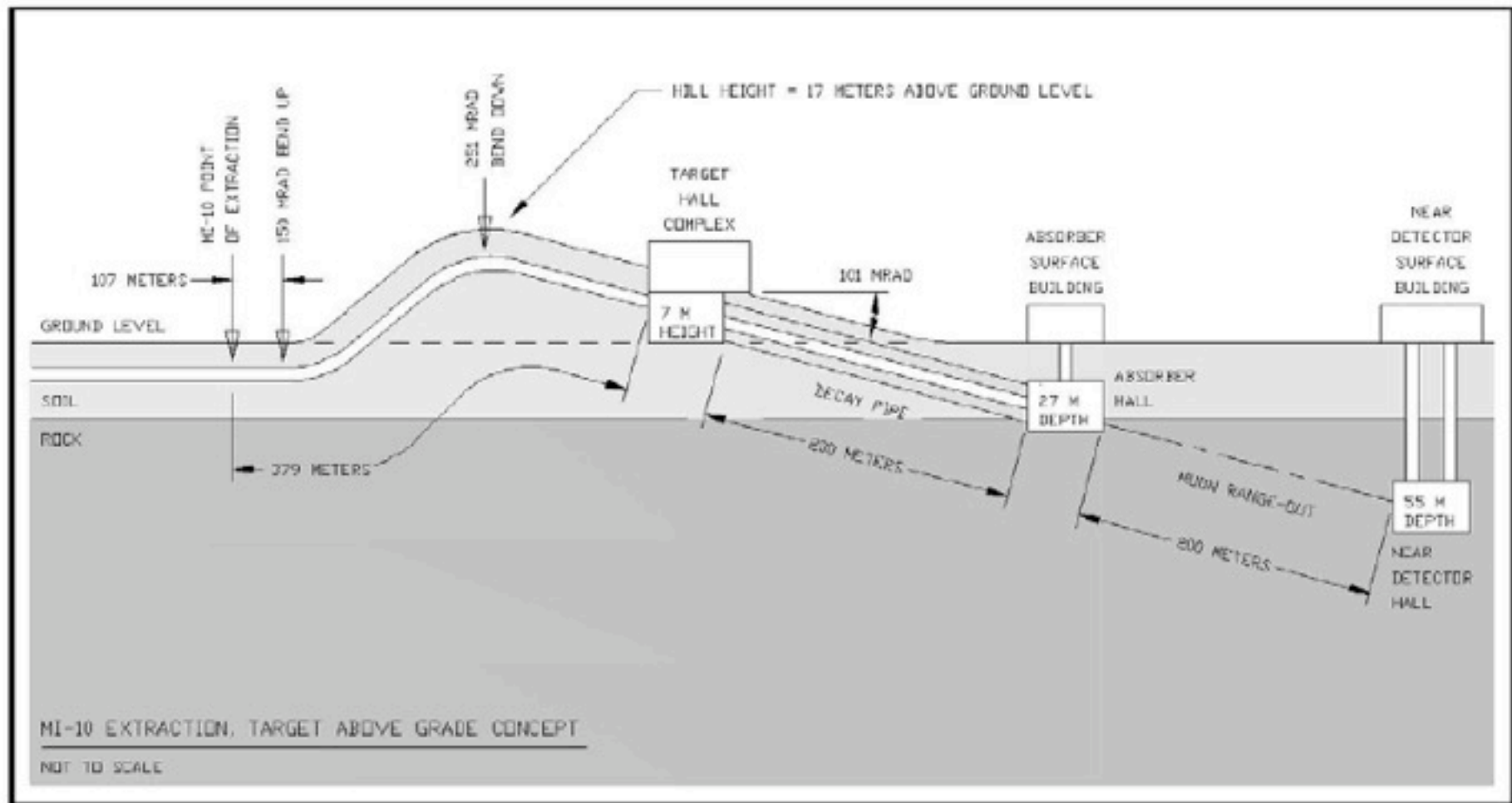


Primary beam energy (protons from the Main Injector) from 60 to 120 GeV

Design is becoming quite detailed and documented



# New above ground design at FNAL



**Fig. 1: LBNE neutrino beam configuration for extraction at MI-10 and the target hall above grade**



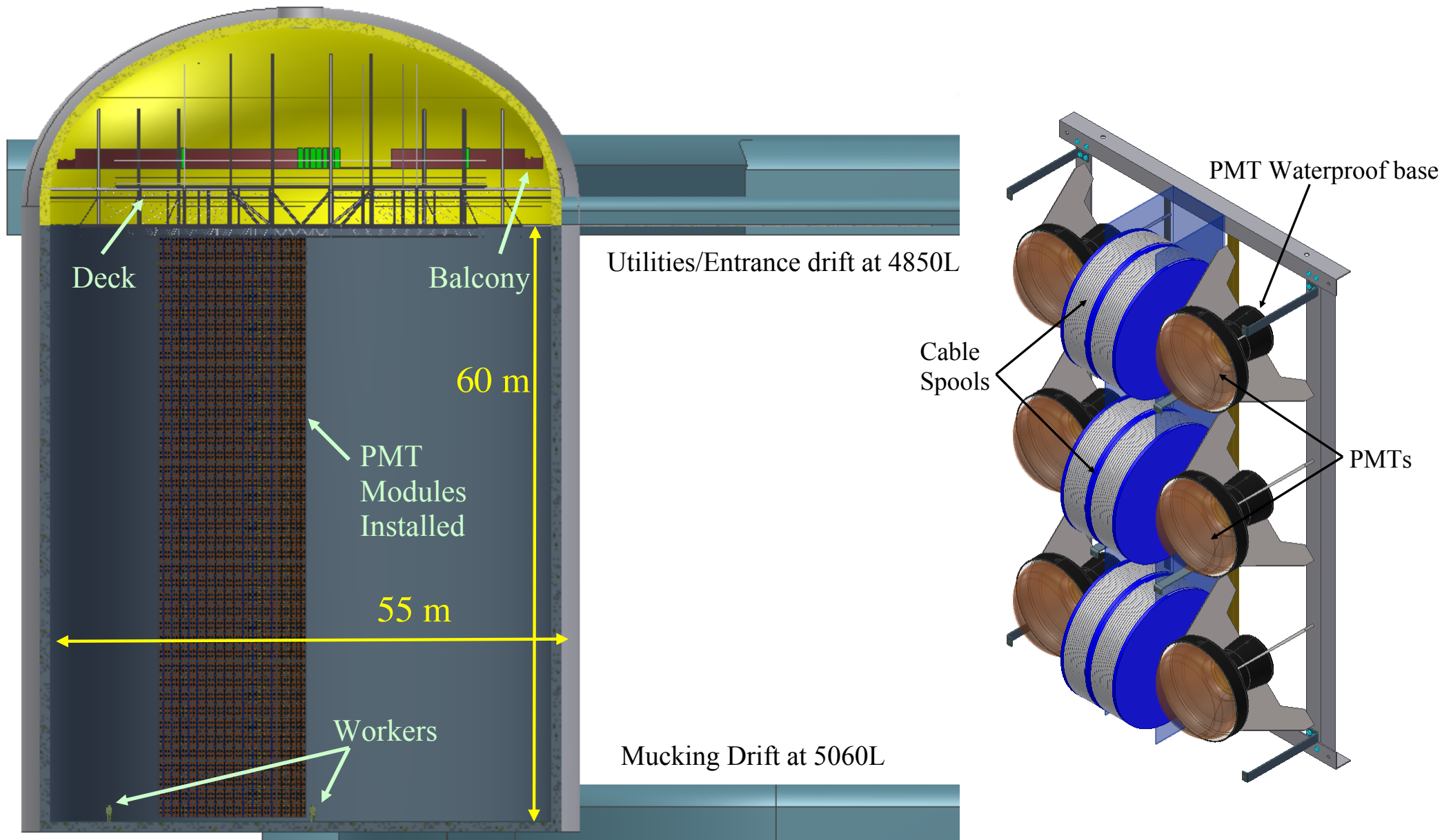








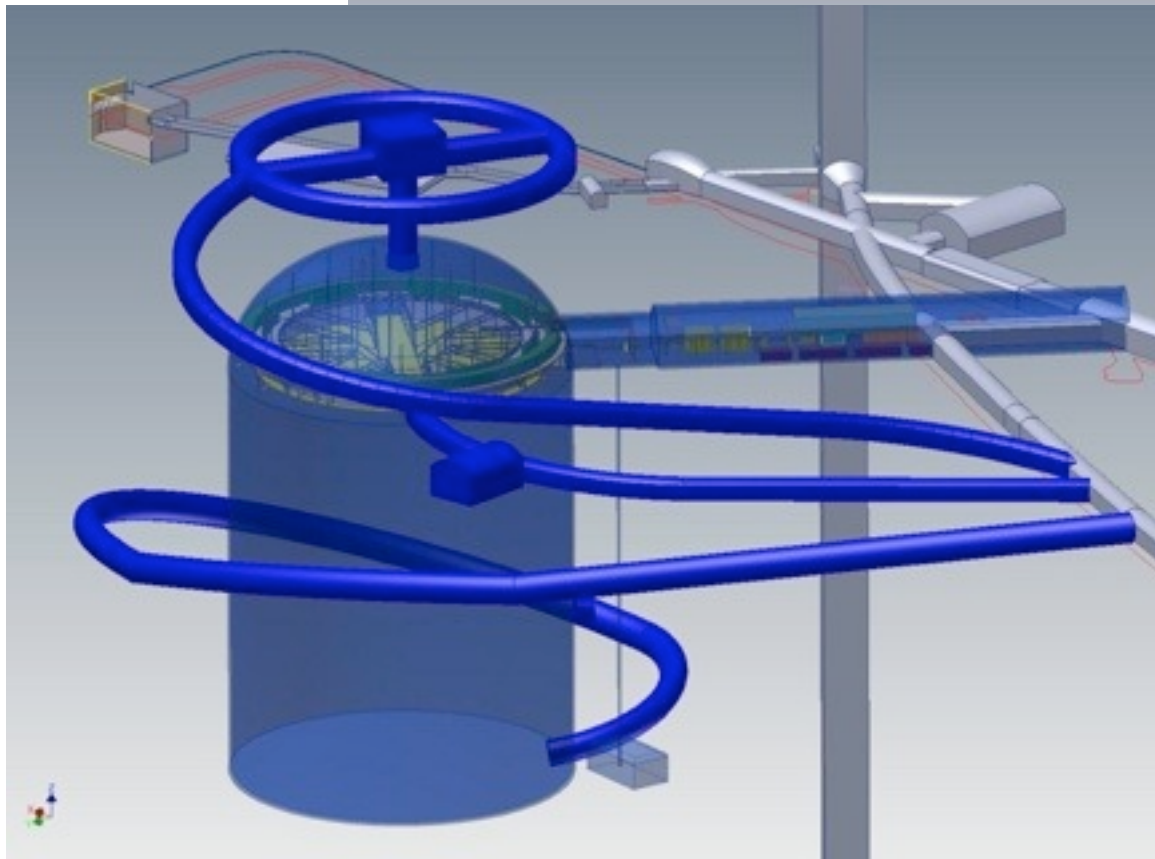
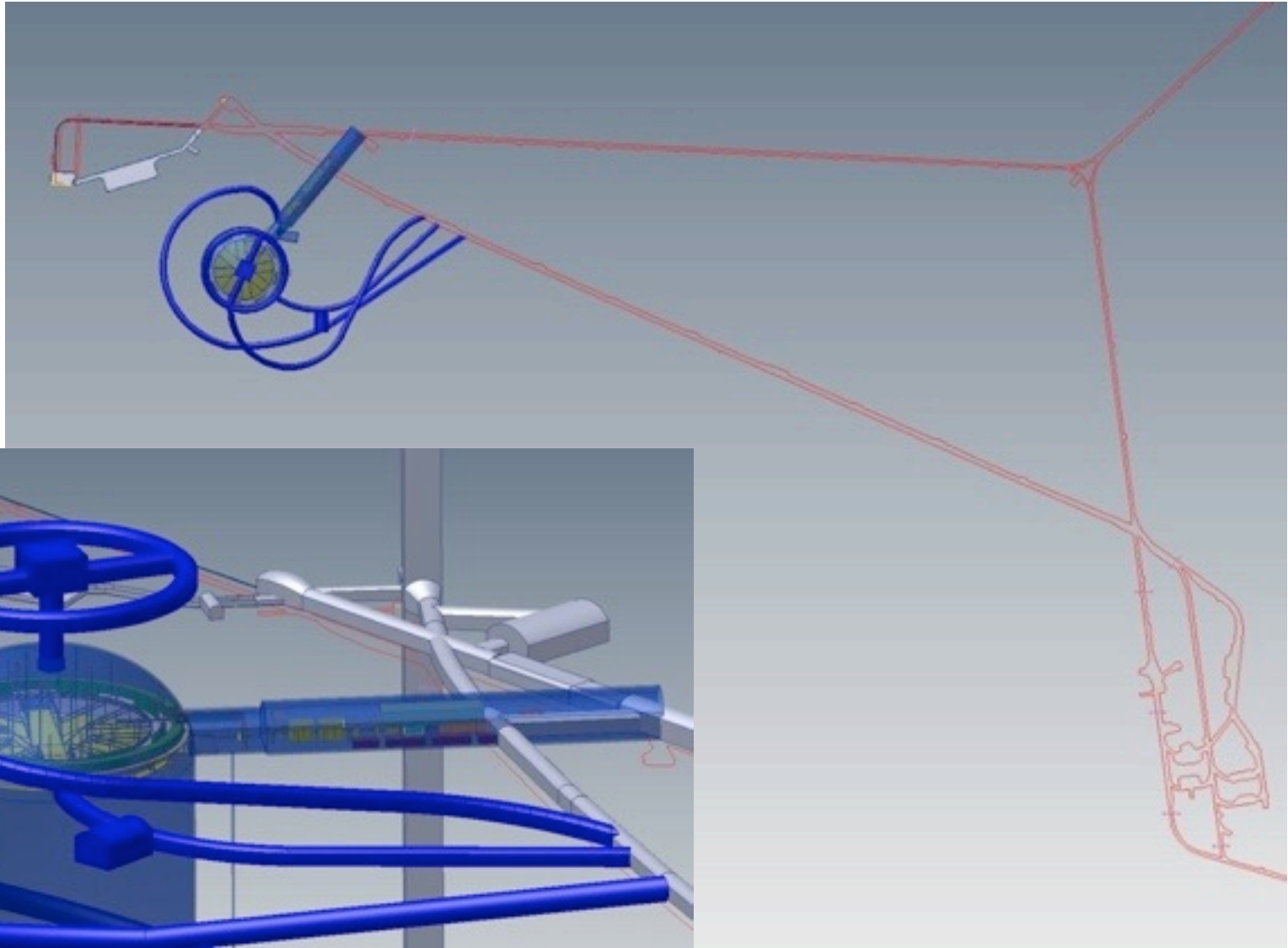
# Water Cherekov Detector: 2 modules of 100 kton each with ~50000 PMTs each



Rather detailed simulation exists due to simulation group led by C.Walter and Ion Stancu



# New underground plan: single 200 kTon detector

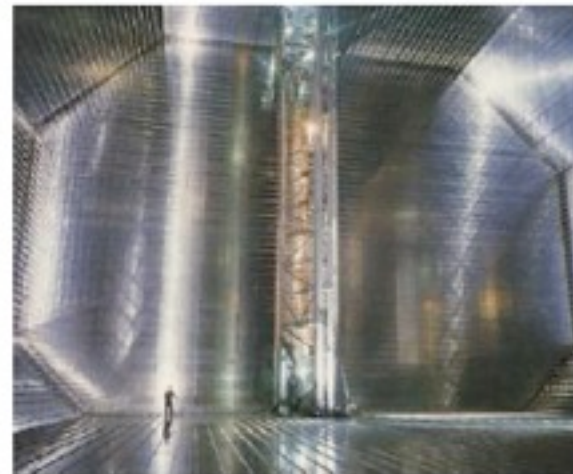


29000 12 inch tubes  
Installed on steel  
cables



# Liquid argon detector

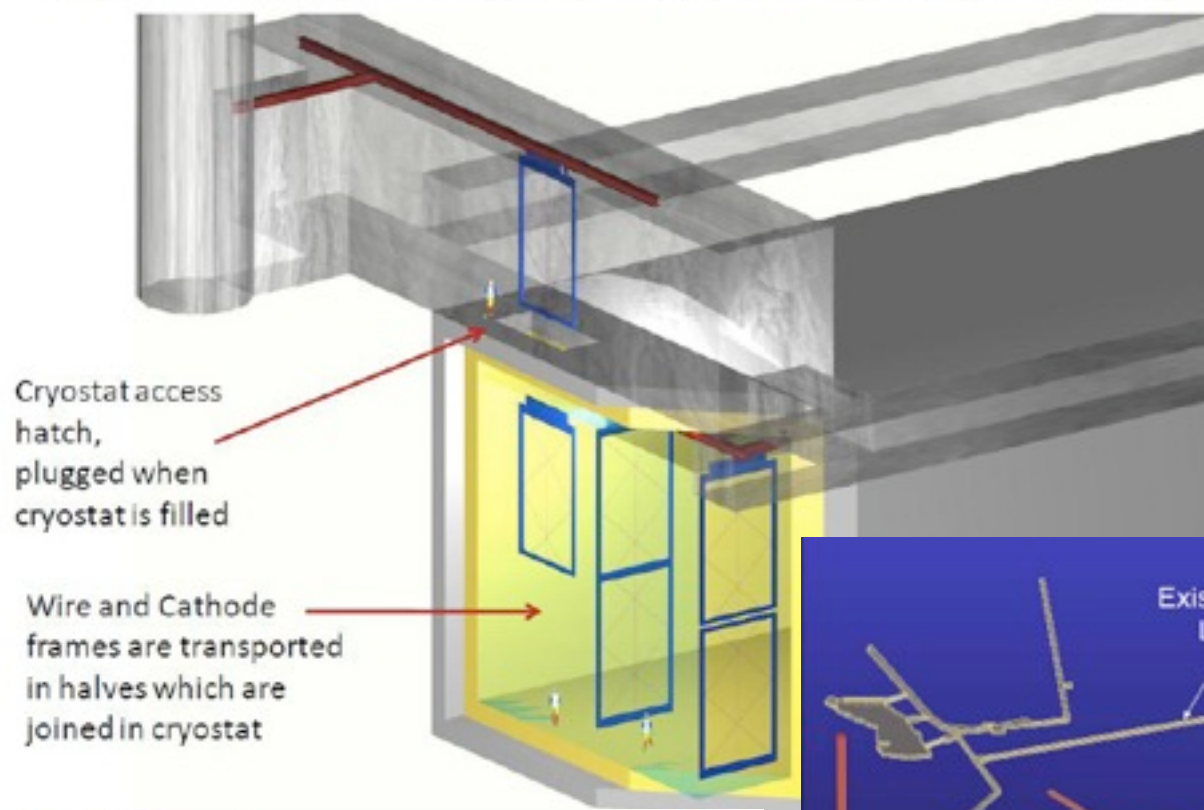
- ▶ Agreed on a preferred design
  - ▶ Reference Design3a – membrane cryostat with cold electronics
  - ▶ Located on the 800 level
  - ▶ Cosmic ray veto
  - ▶ Agreed on 3mm wire spacing
  - ▶ Agreed on three wire planes + 1 un-instrumented grid plane
  - ▶ Details given in Reference Design talk



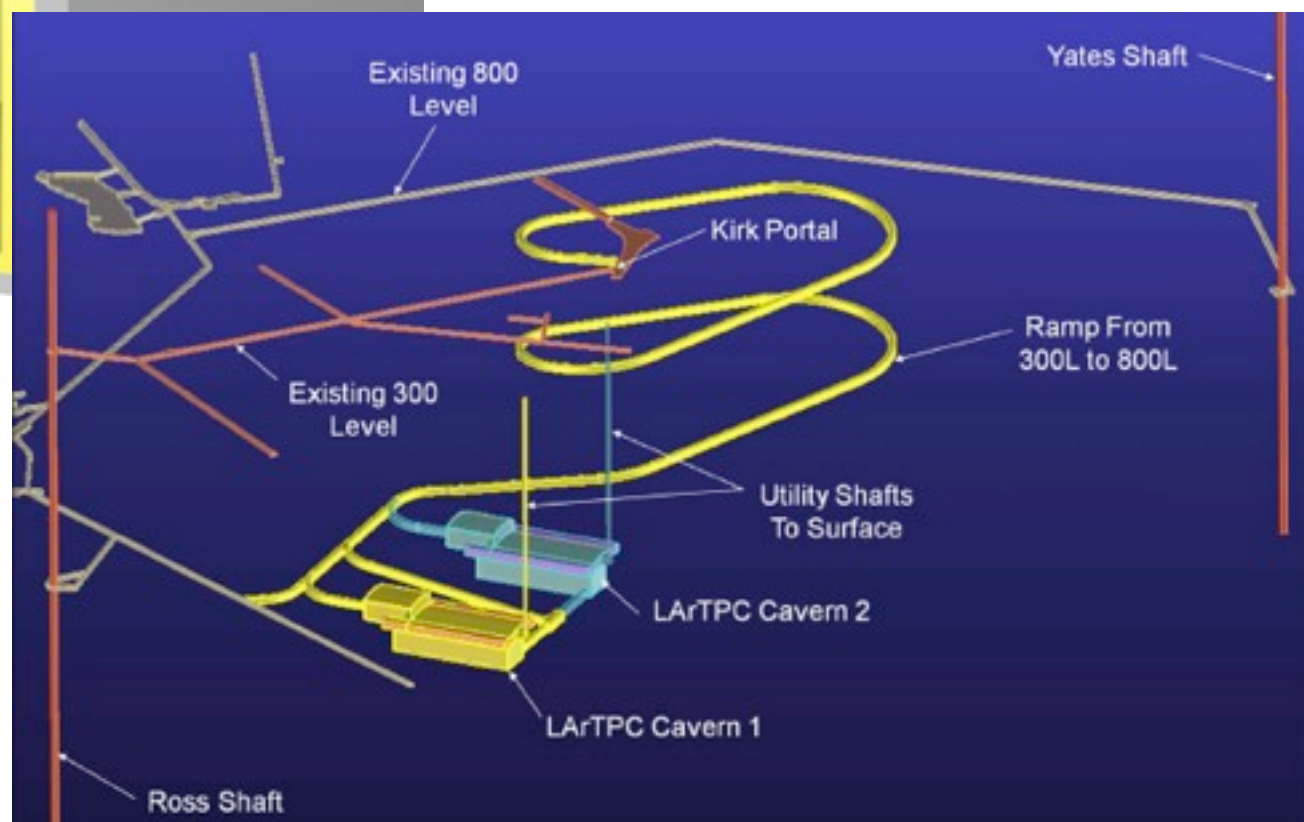
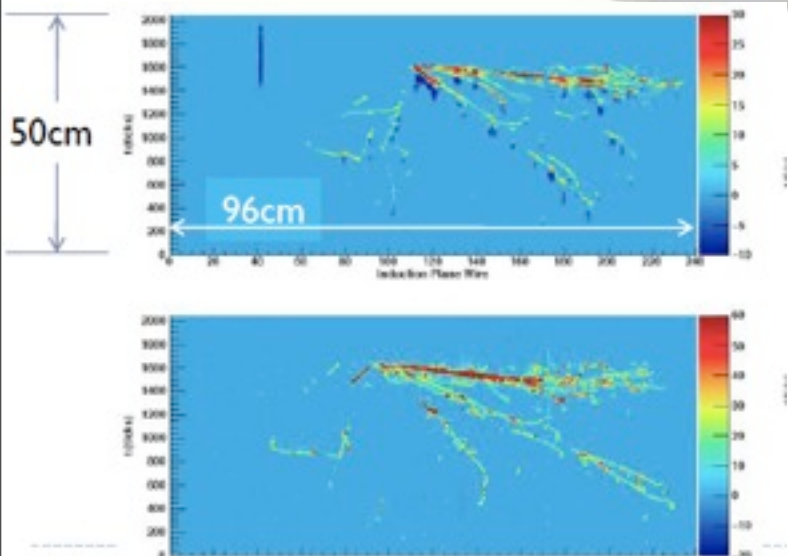
Baller



Cryostat end cut open to show frame assembly



800 ft depth with  
an active veto shield.  
Simulation and  
performance based  
on Argoneut

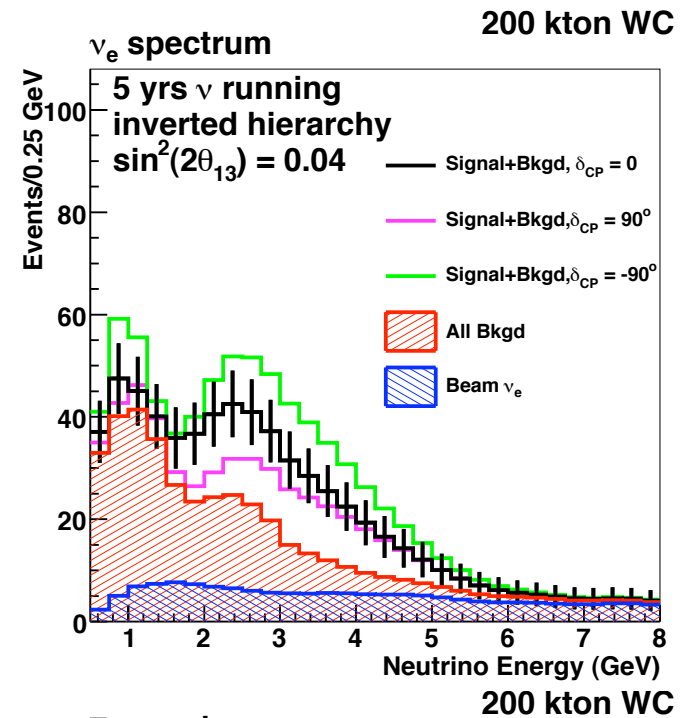
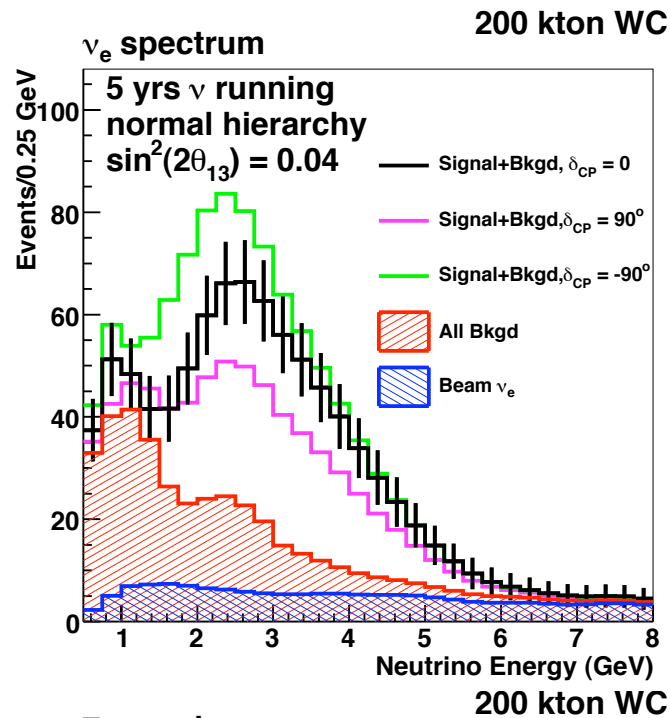




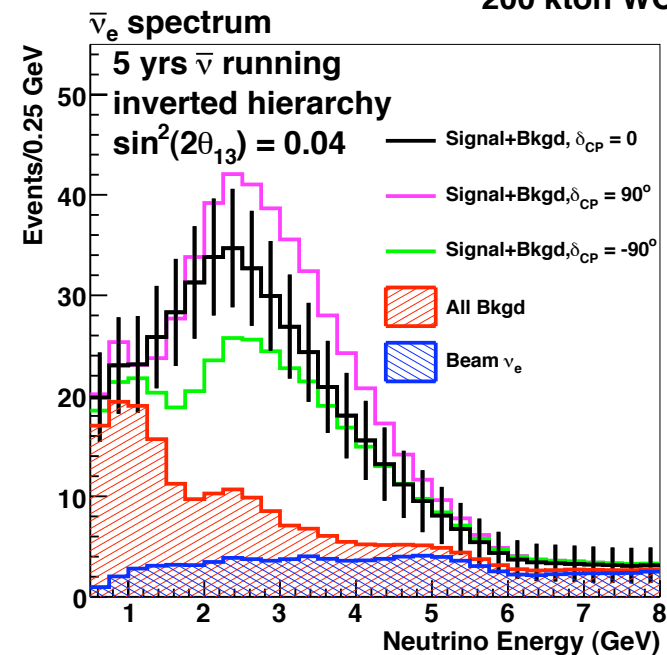
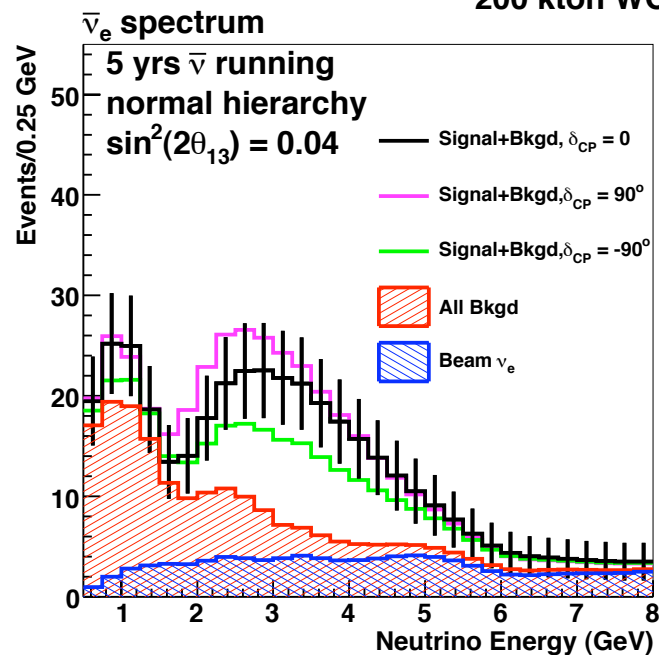
# normal

# inverted

nu



anti-nu



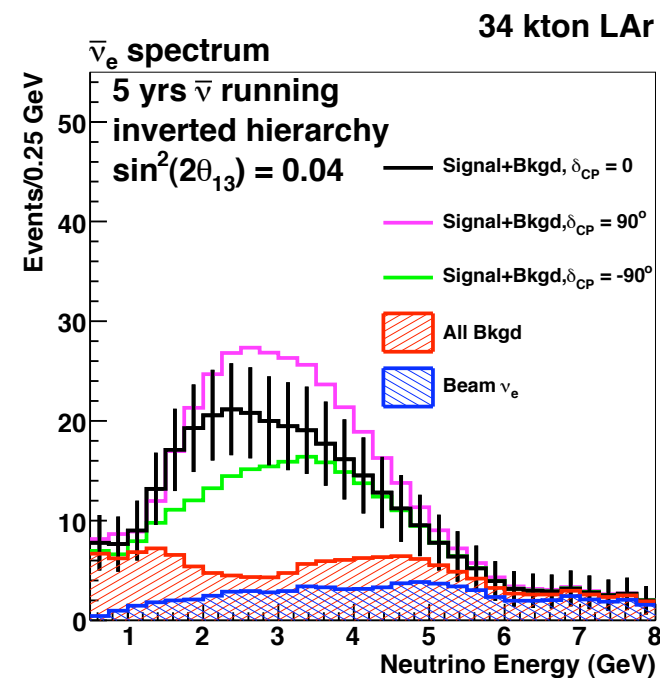
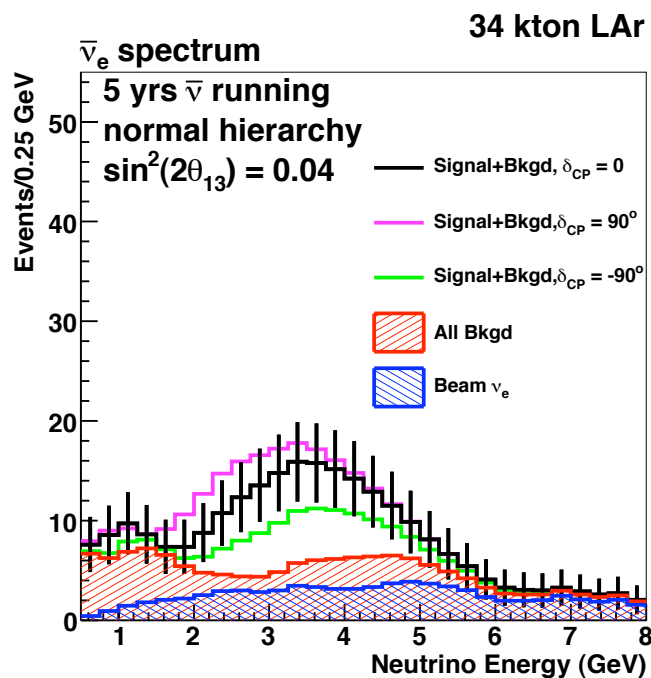
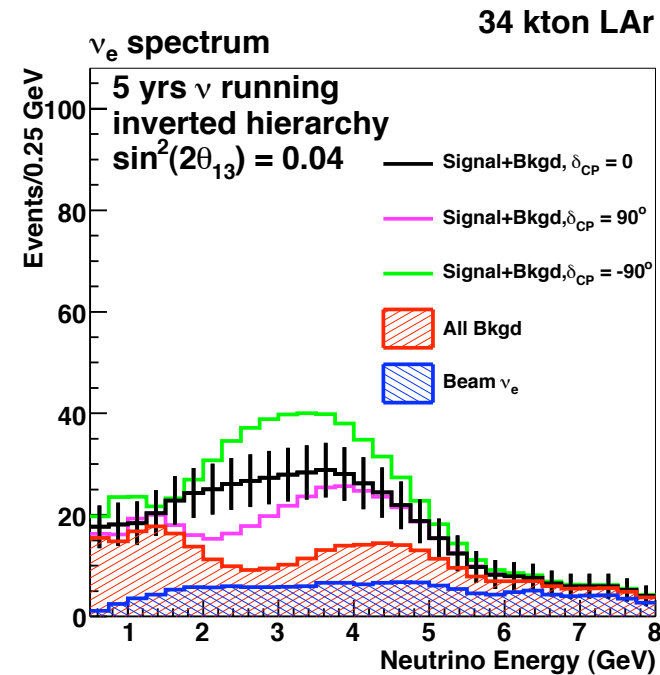
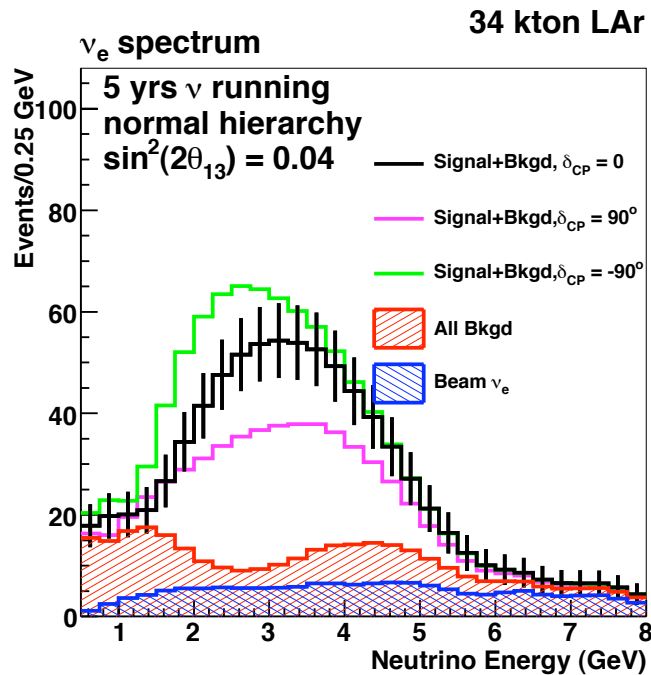
Lisa Whitehead



# normal

# inverted

nu

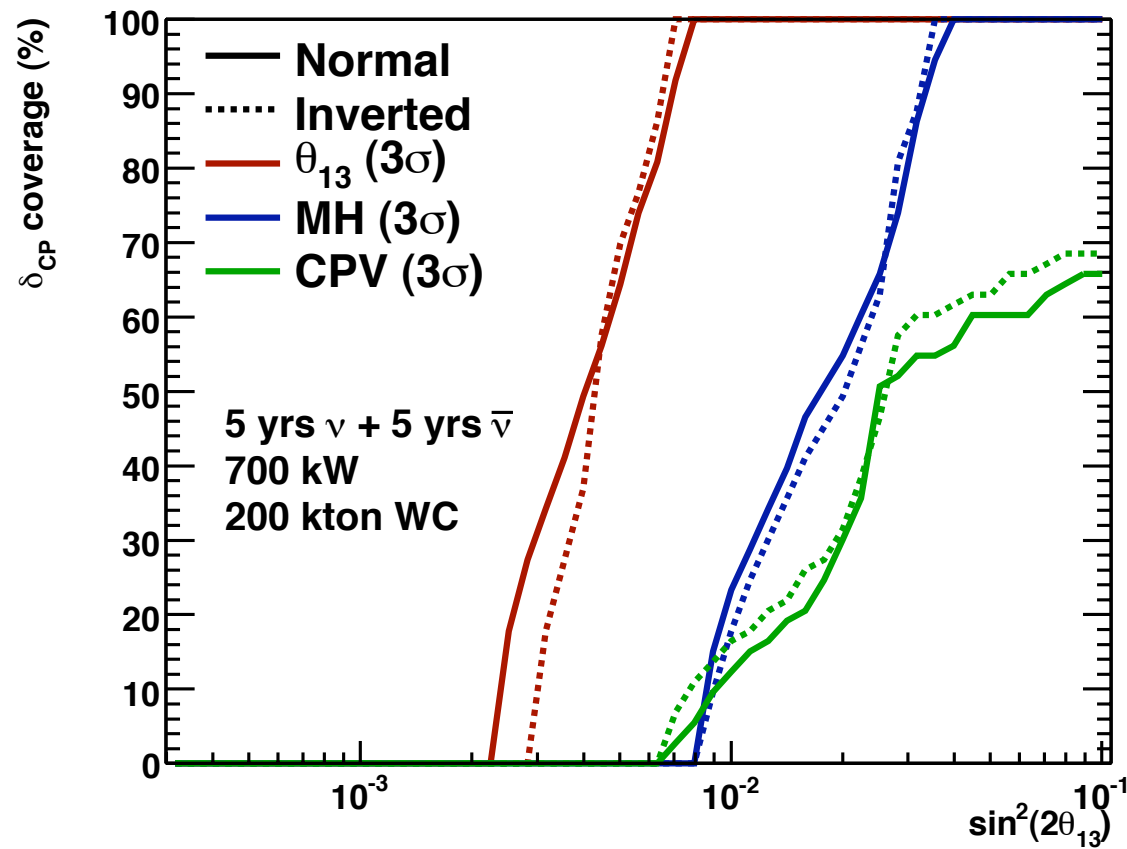


anti-nu

Lisa Whitehead



# Sensitivity summary





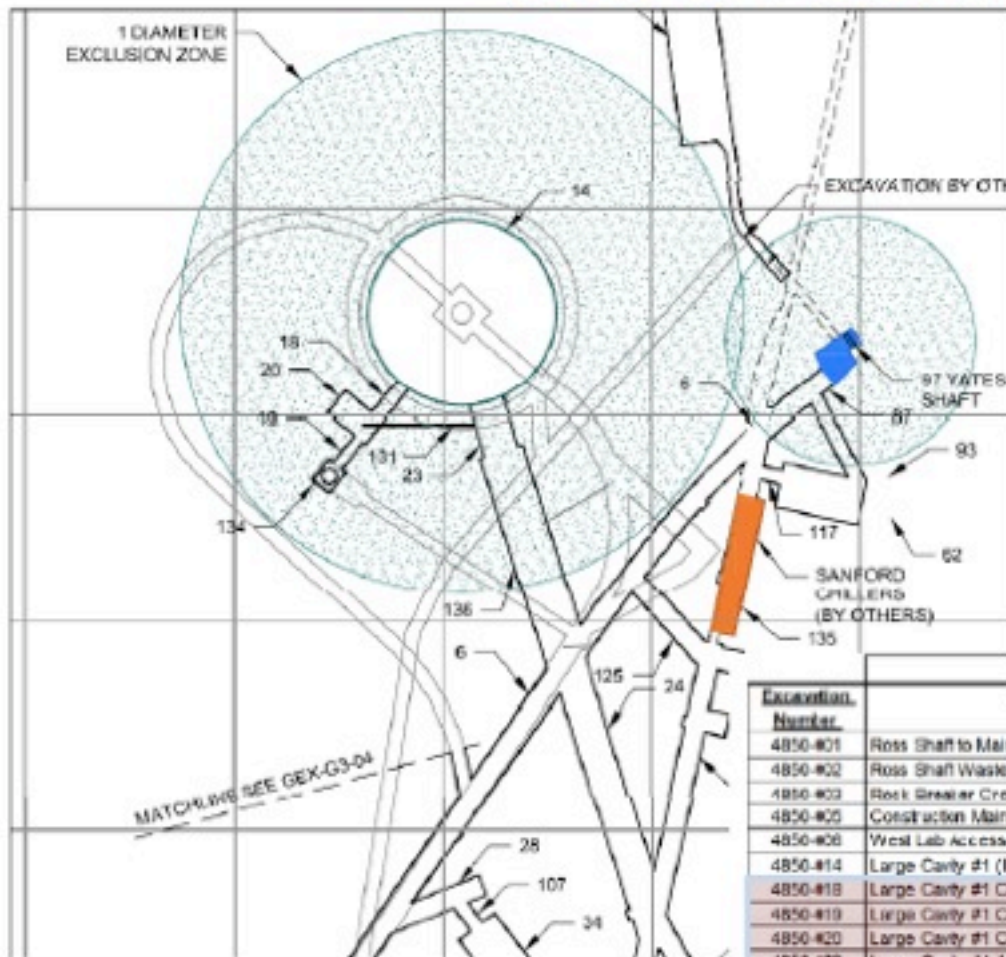
# Summary

- Discovery of oscillations and neutrino mass has opened a new field for measurement.
- The current focus is on full understanding of the quantum mechanical mixing phenomena which takes place on a very large scale and huge dynamic ranges.
- A new program of experiments is in discussion and design. It requires detectors that are order of magnitude bigger and beam intensities that are much higher.



# 4850L LBNE Spaces

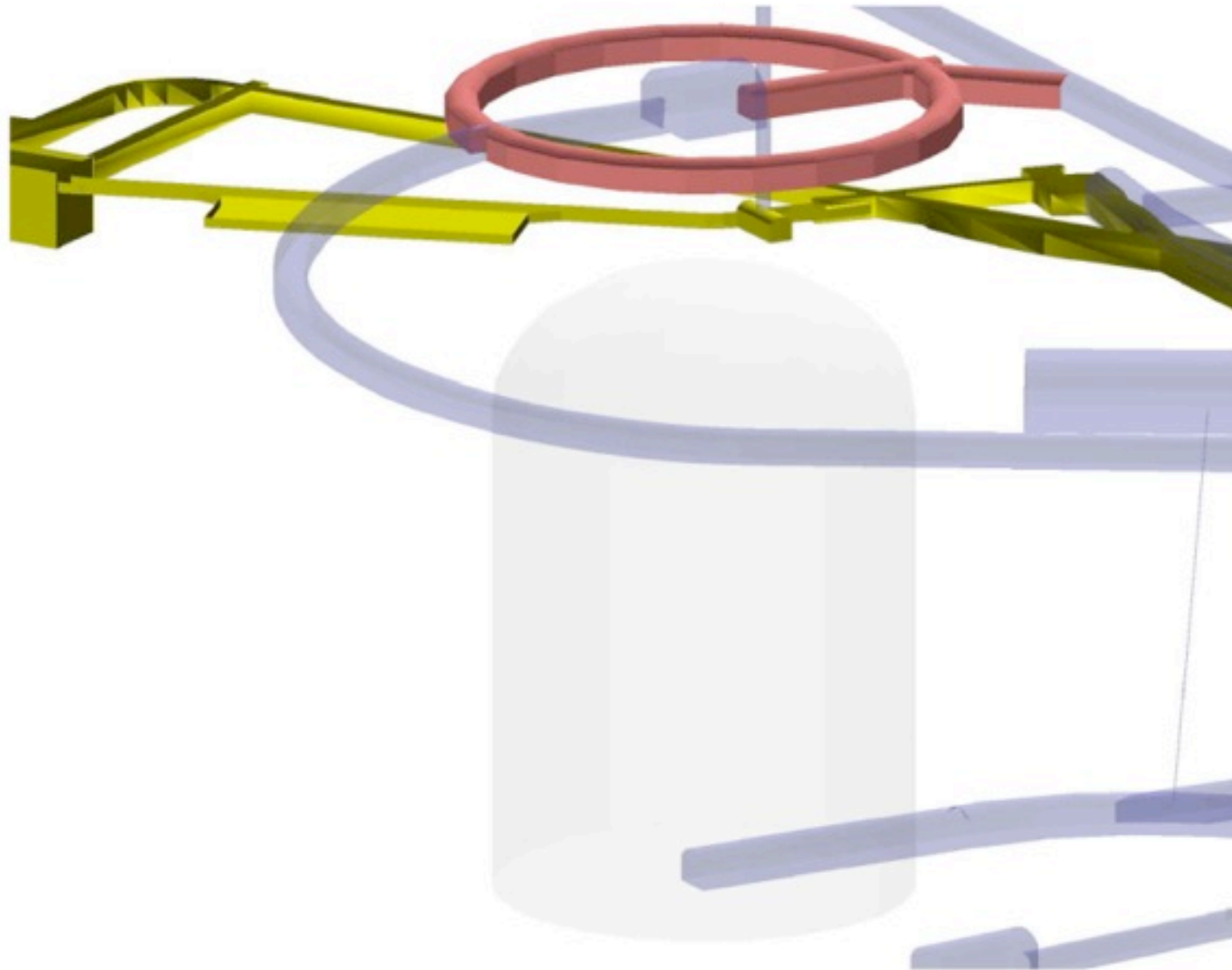
All information from Golder 100% PD draft drawings dated 13-Sep-2010



Excavation Number	DUBEL WREPC Slope Excavation Name	90% PDR - Finished Inside Dimensions, Metric			
		Width (m)	Height (m)	Length (m)	Springline (m)
4850-401	Ross Shaft to Main Access Drift	6.00	6.00	201.02	4.50
4850-402	Ross Shaft Waste Dump Drift	8.00	7.00	10.97	5.00
4850-403	Rock Breaker Cross Cuts	8.00	7.00	15.83	5.00
4850-405	Construction Maintenance/Assembly Shop	13.08	8.25	20.03	5.00
4850-406	West Lab Access Drift	6.00	6.00	744.56	4.50
4850-414	Large Cavity #1 (Including Dome)	55.08	83.00	0.00	64.00
4850-418	Large Cavity #1 Calibration Drift	4.00	4.00	20.15	3.00
4850-419	Large Cavity #1 Calibration Drift Access	3.00	3.00	9.85	2.25
4850-420	Large Cavity #1 Calibration Room (Including Access Portal)	8.00	5.00	10.05	3.00
4850-423	Large Cavity #1 Access and Utility Drift	10.08	8.00	14.72	5.50
4850-424	Large Cavity #1 Access Drift, Water Purification System	10.08	8.00	71.93	5.50
4850-485	4850 - 3950 Vent Raise Access Drift	6.00	6.00	15.15	4.50
4850-486	4850 - 3950 Vent Raise (round)	4.27		207.24	
4850-131	LC1 Utility borehole	0.30		32.75	
4850-39	Yates Shaft Emergency Response Equipment Storage	0.00	0.00	0.00	0.00
4850-36	Large Cavity #1 Access and Utility Drift - Enlarged section	13.08	8.75	60.91	4 5.50

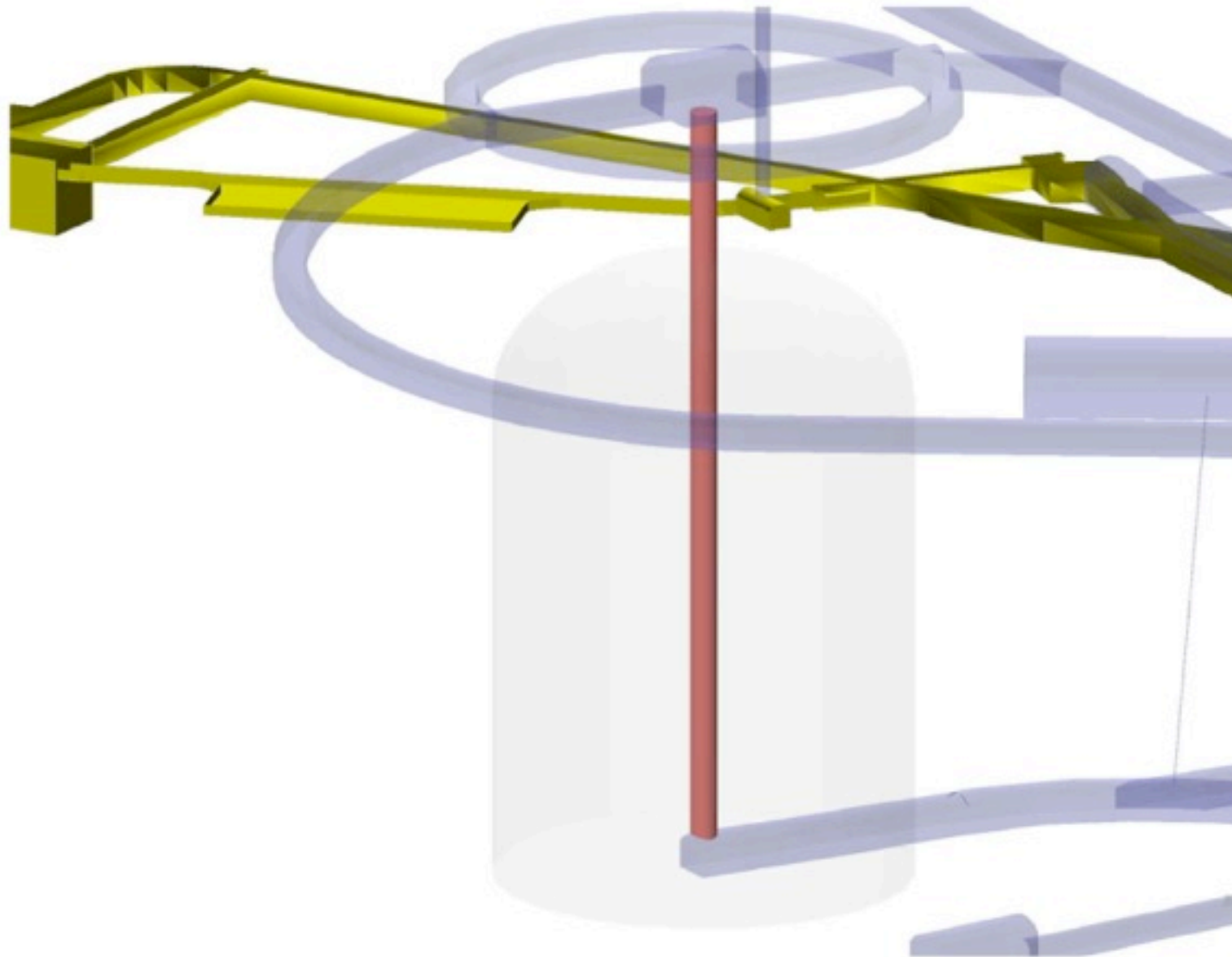


# LC-1 Excavation & Support



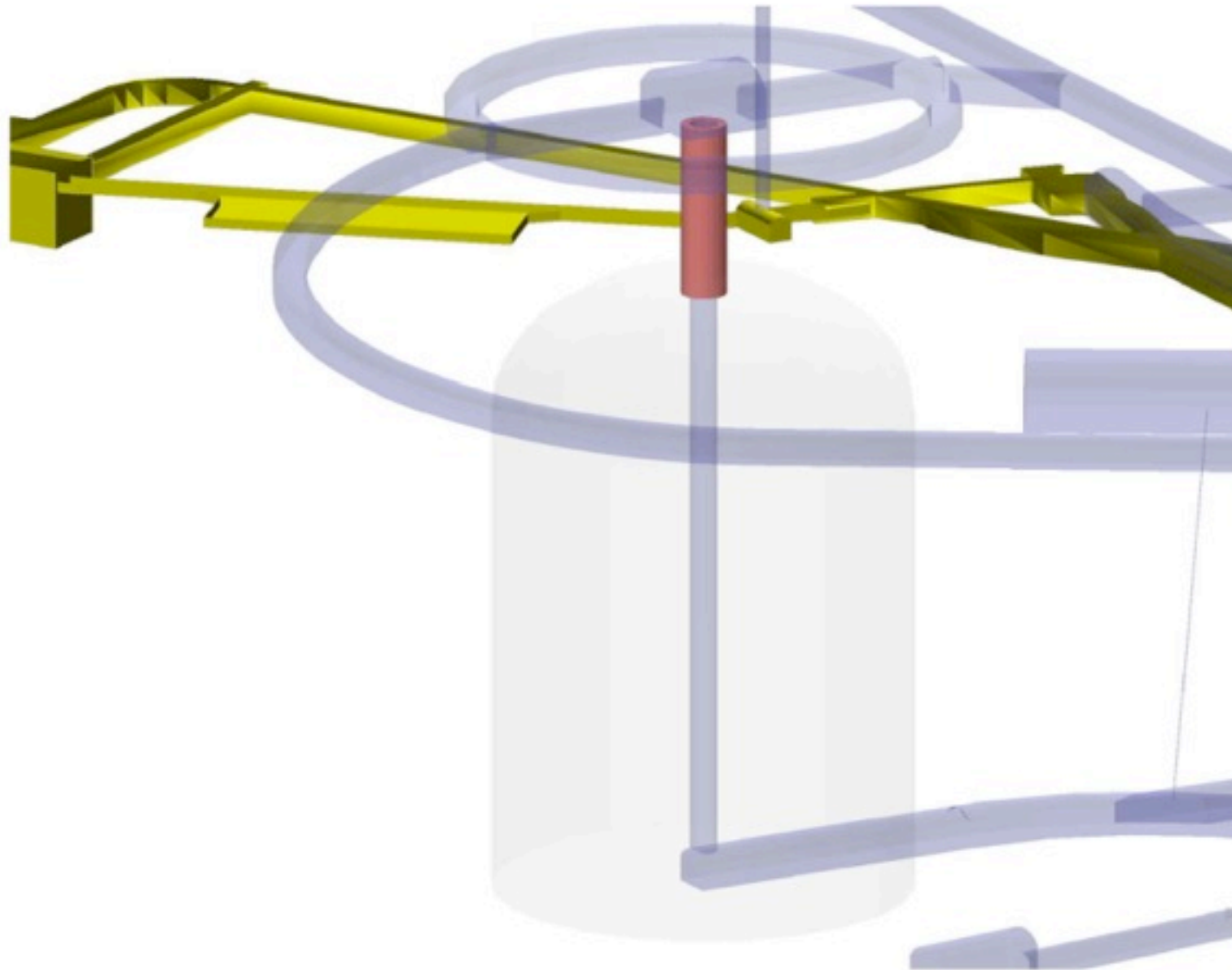


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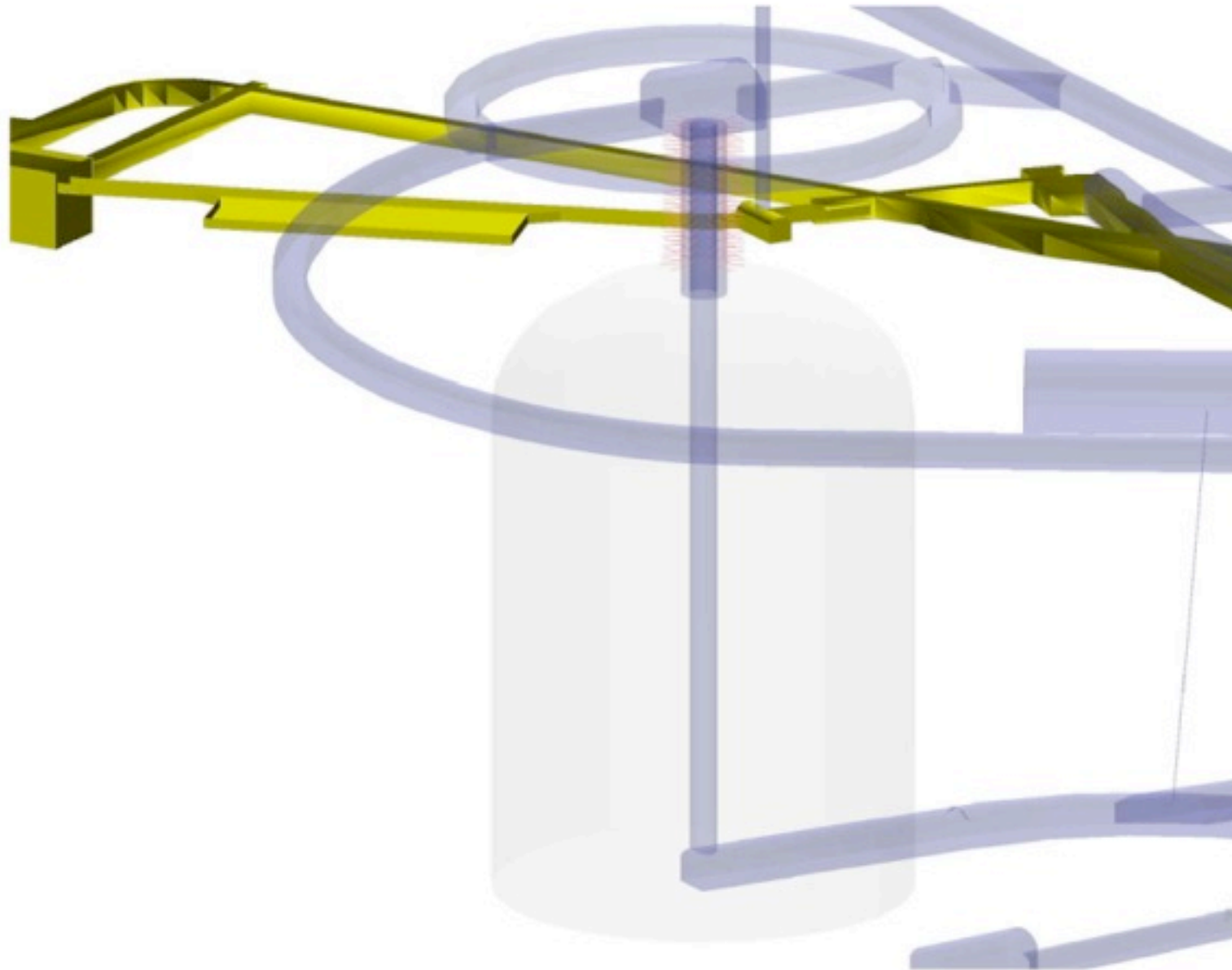


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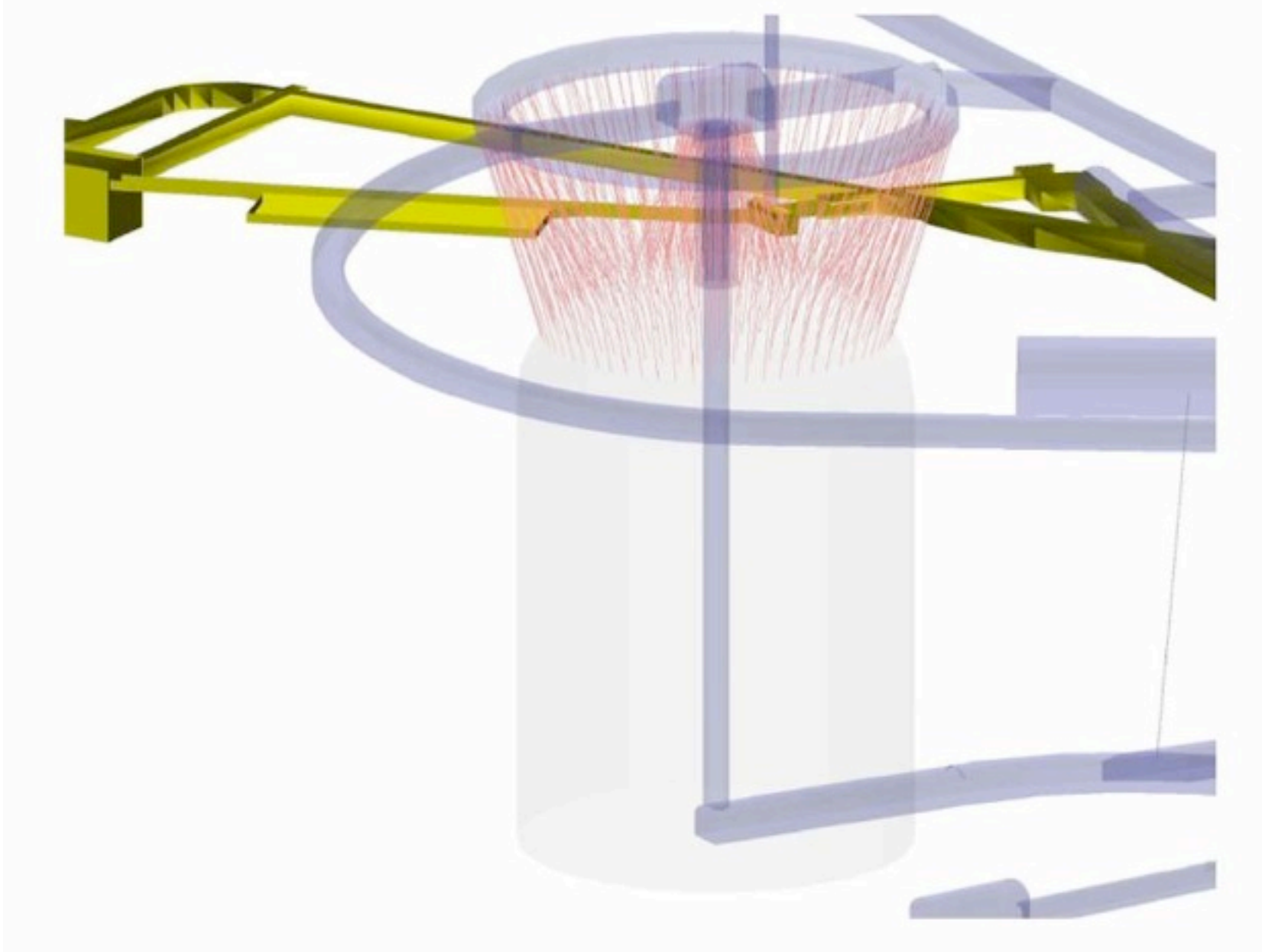


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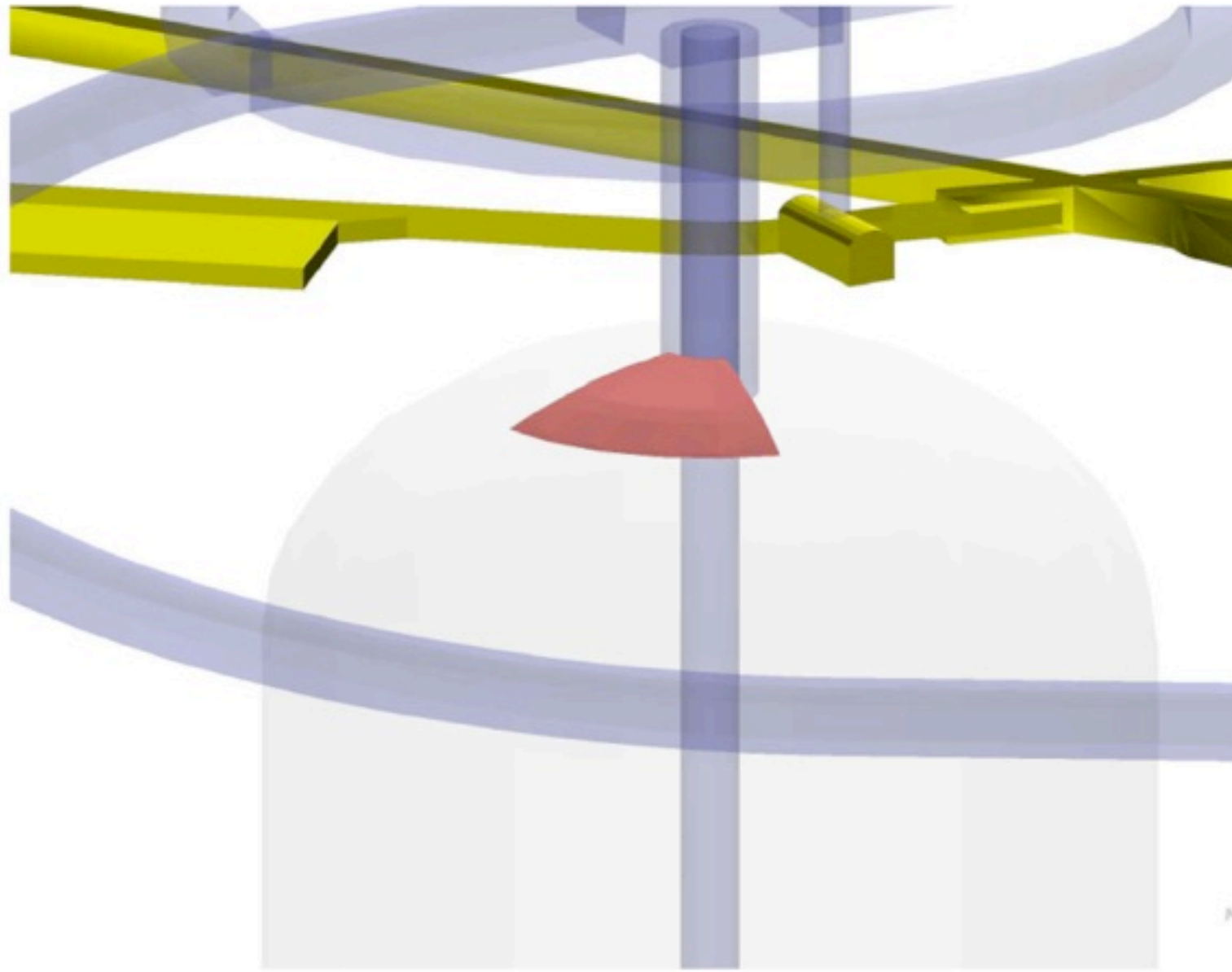


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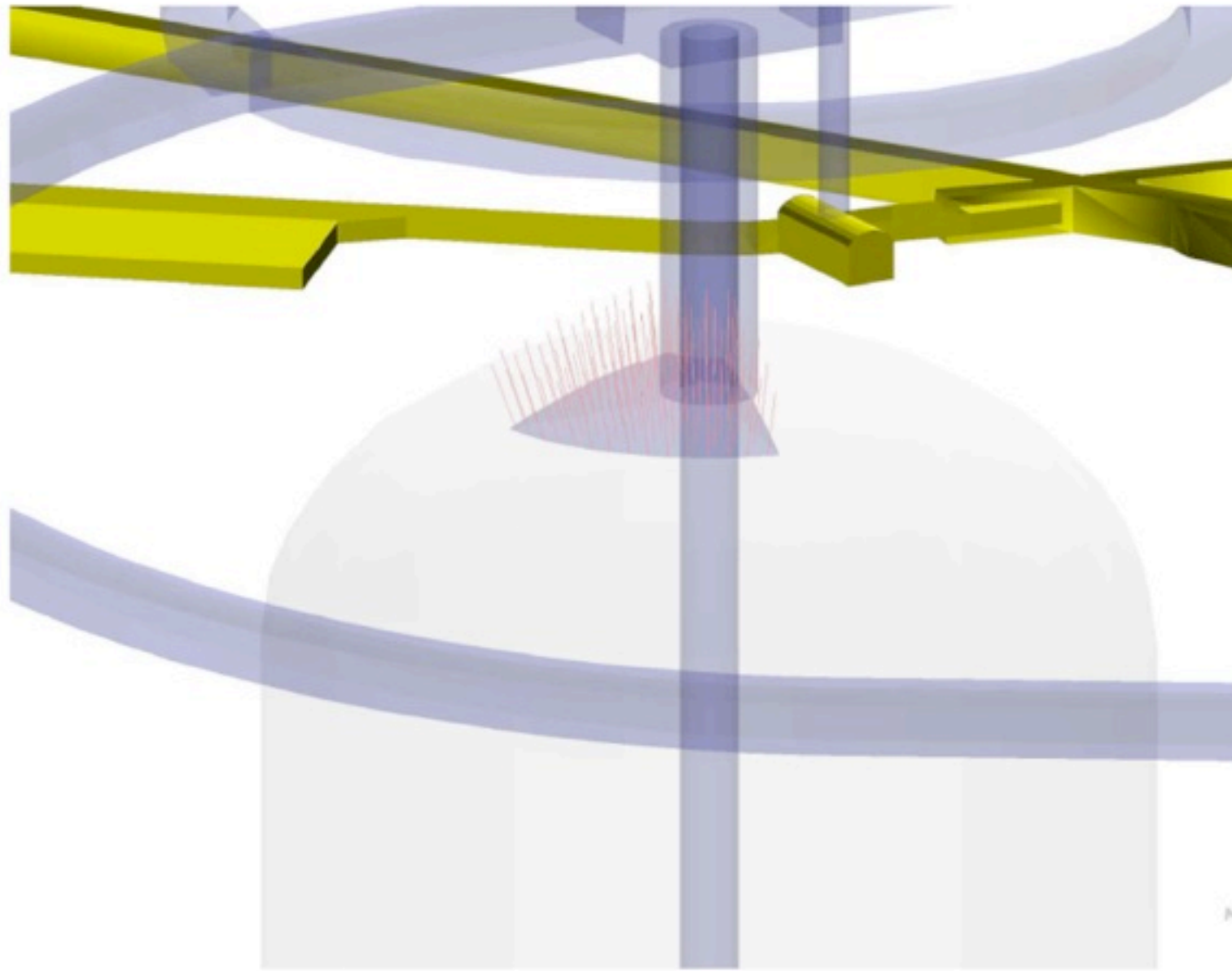


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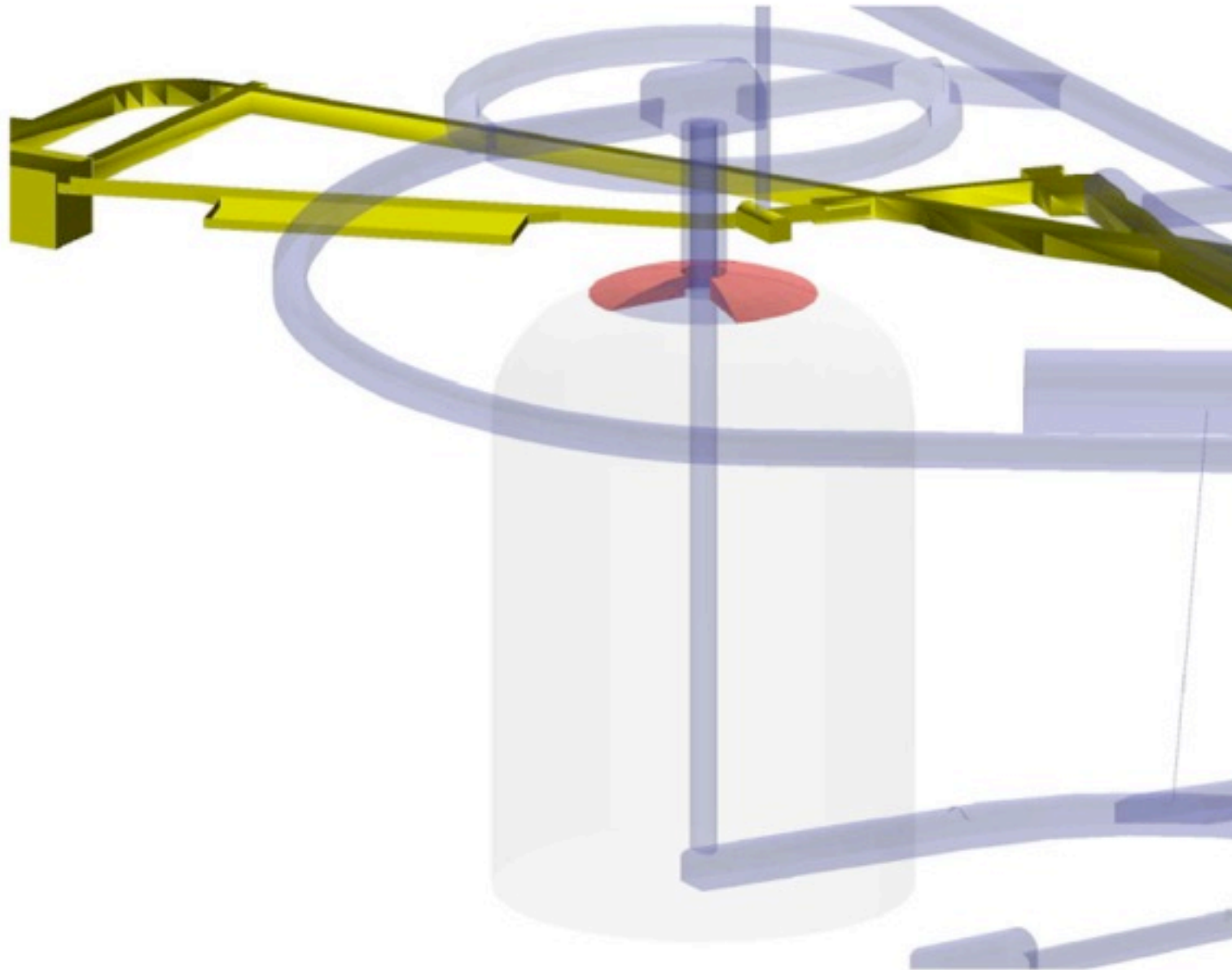


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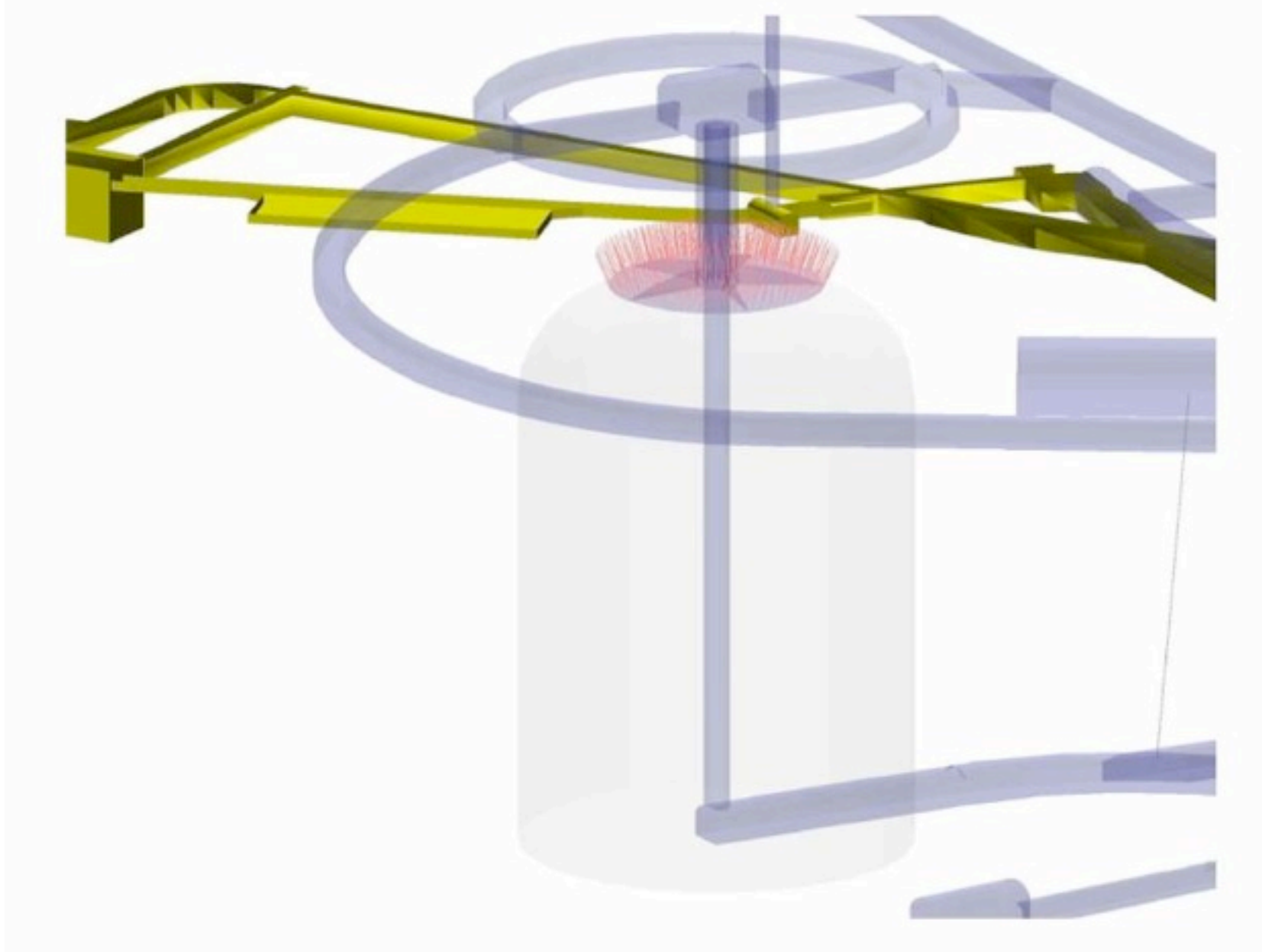


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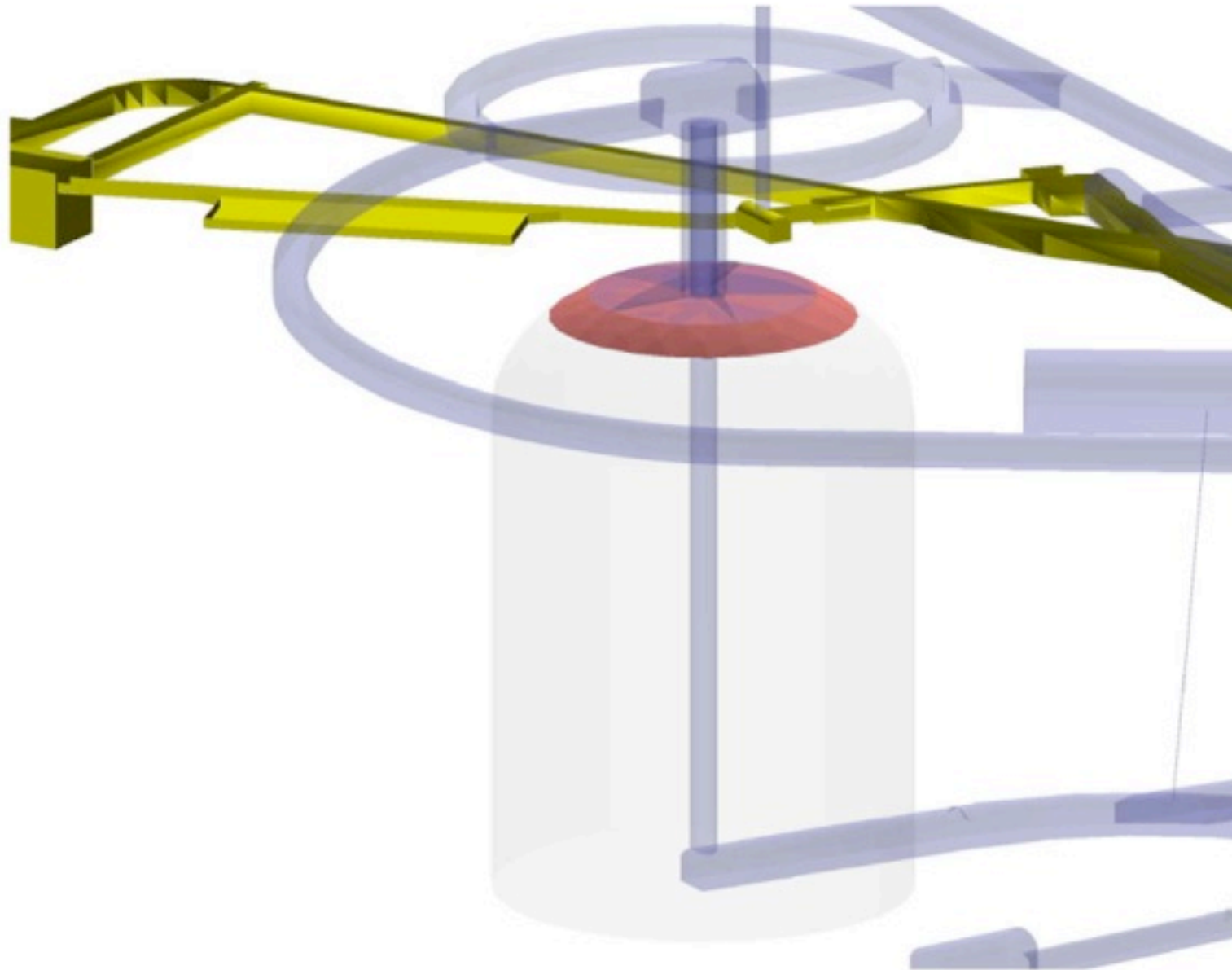


# LC-1 Excavation & Support



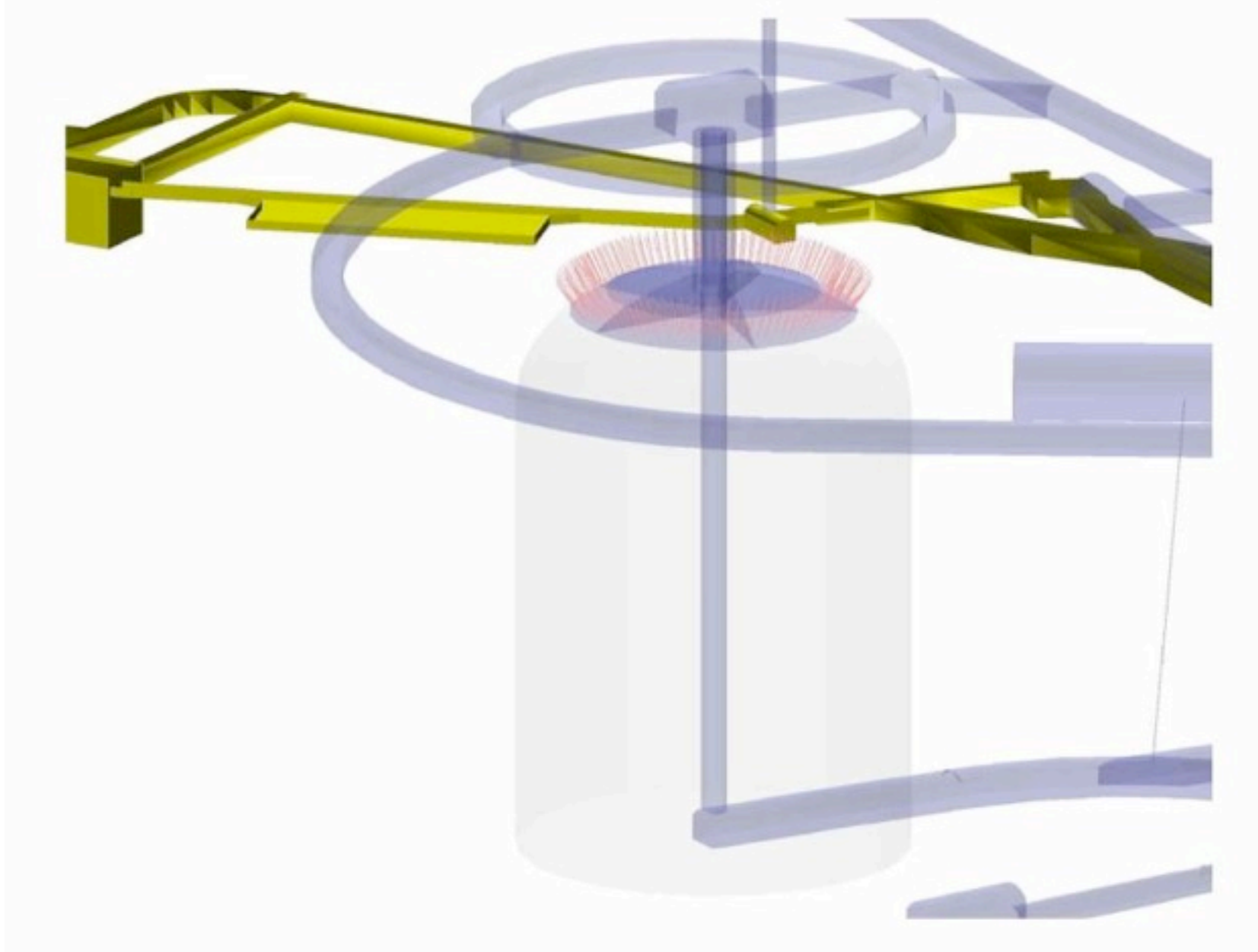


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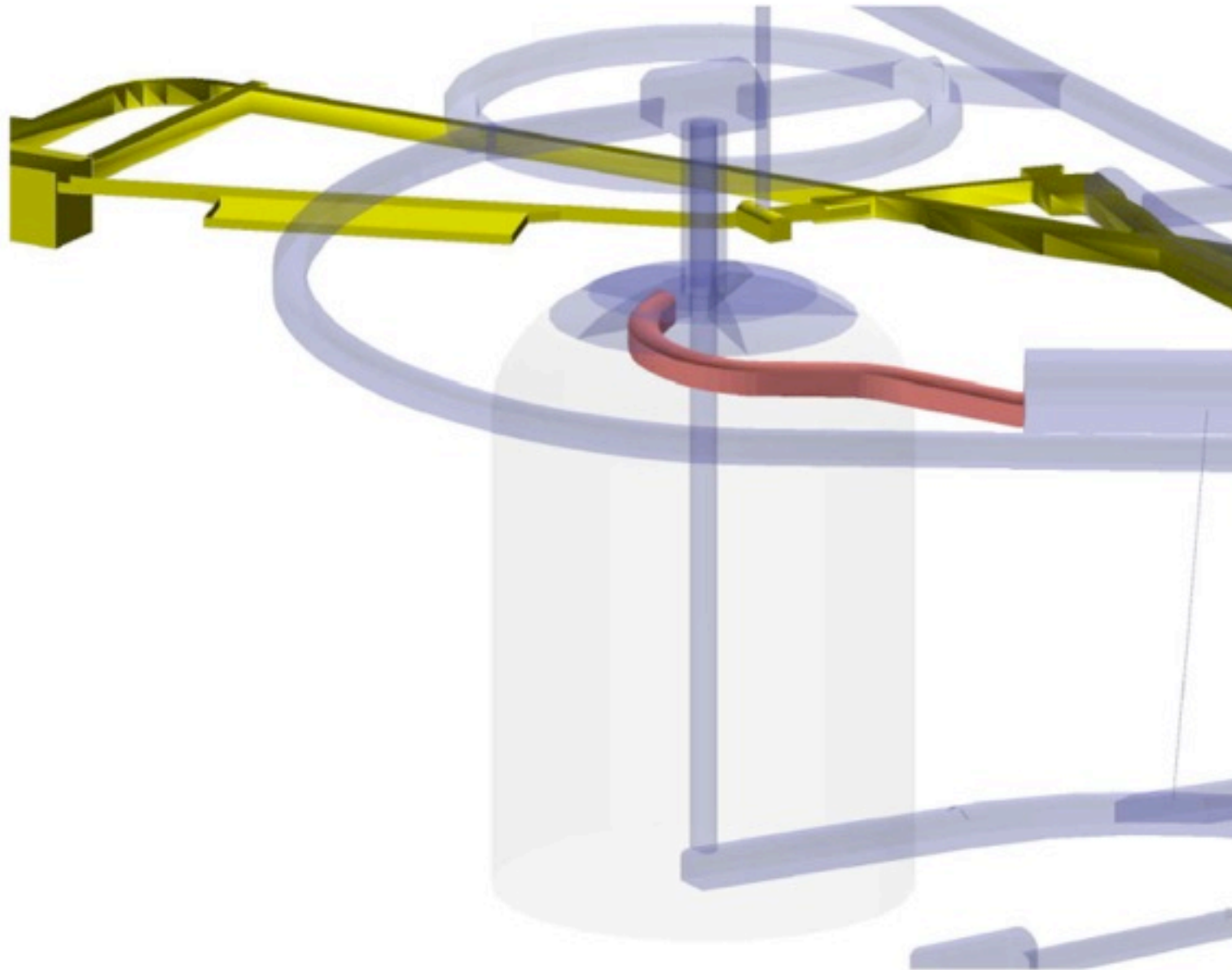


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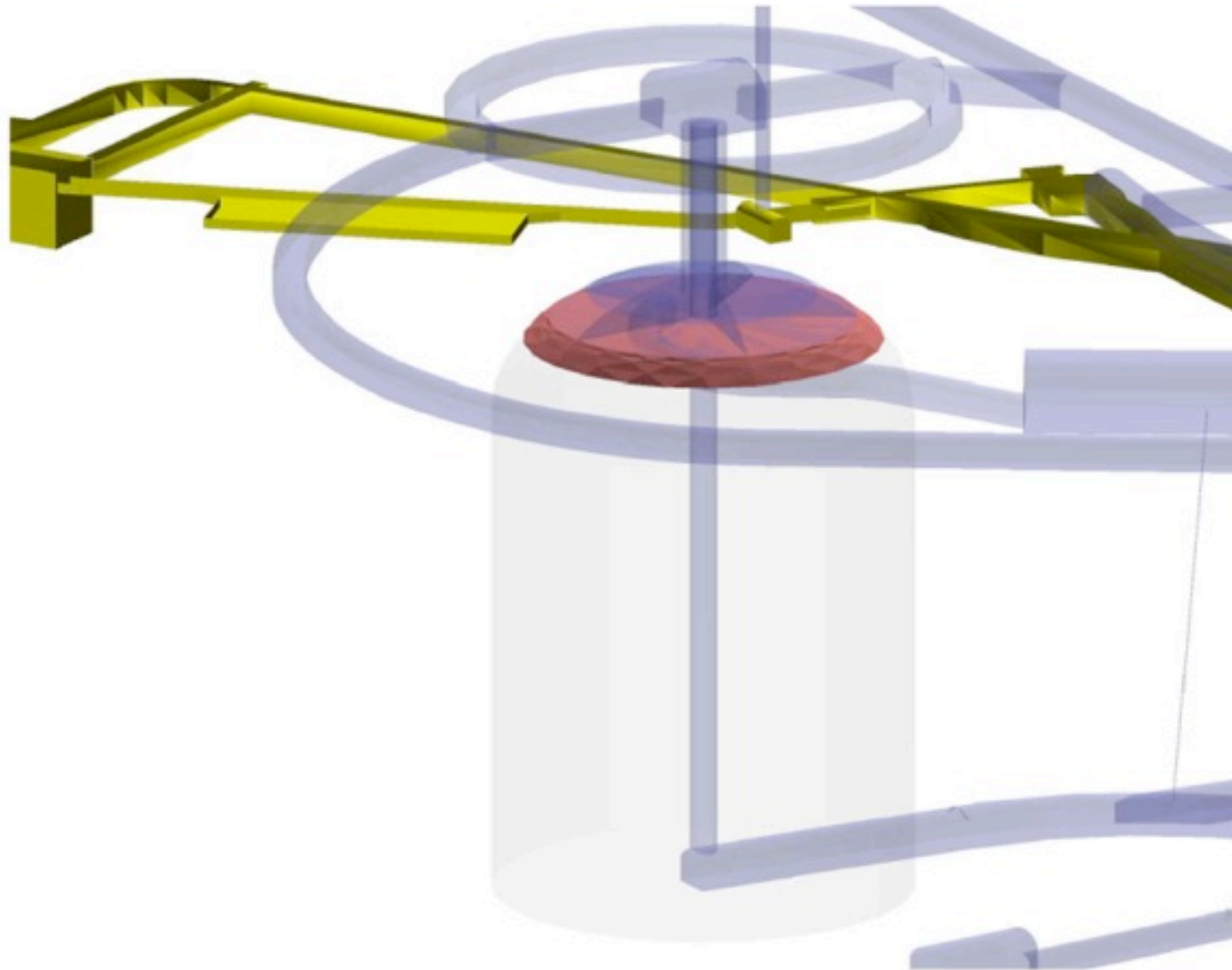


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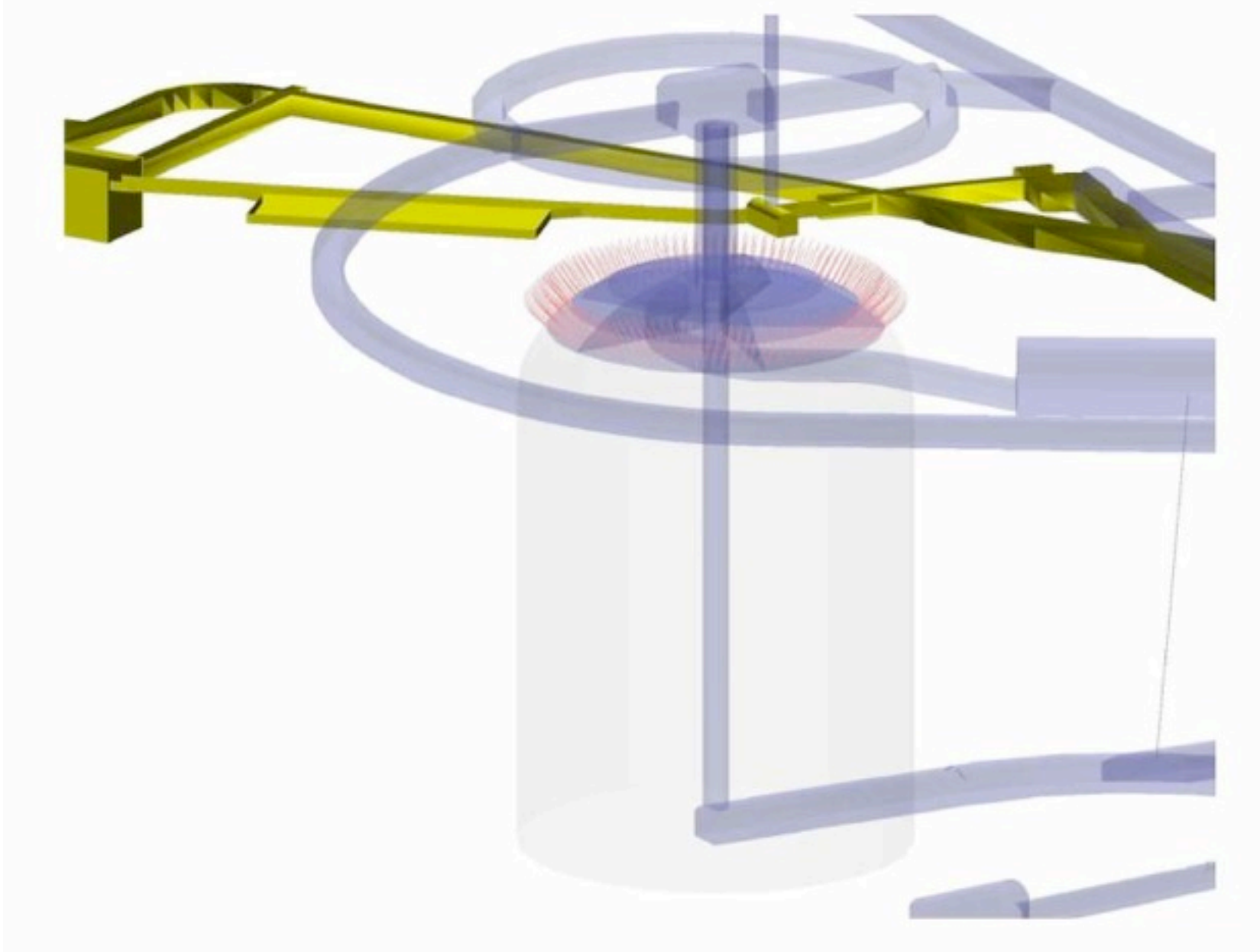


# LC-1 Excavation & Support



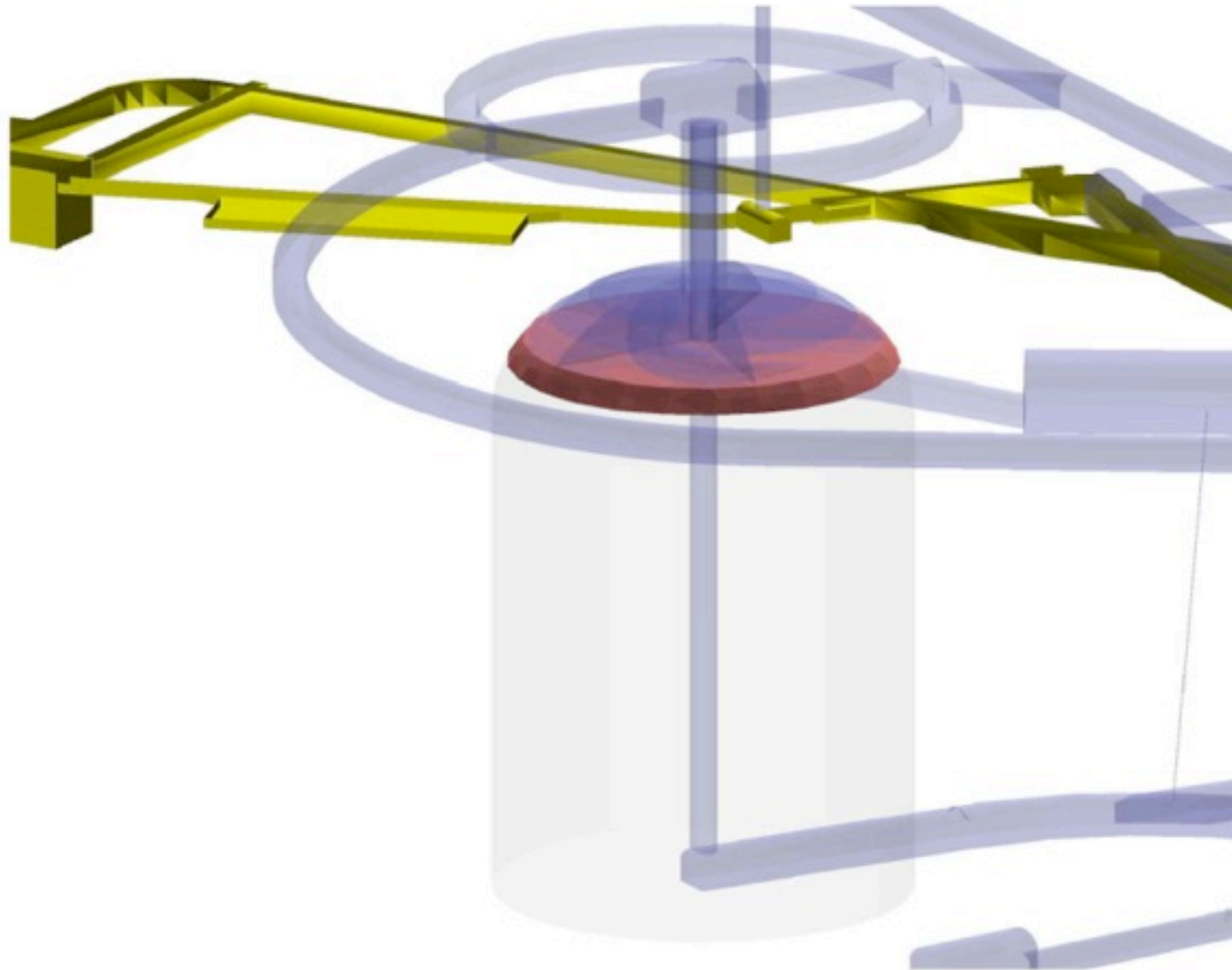


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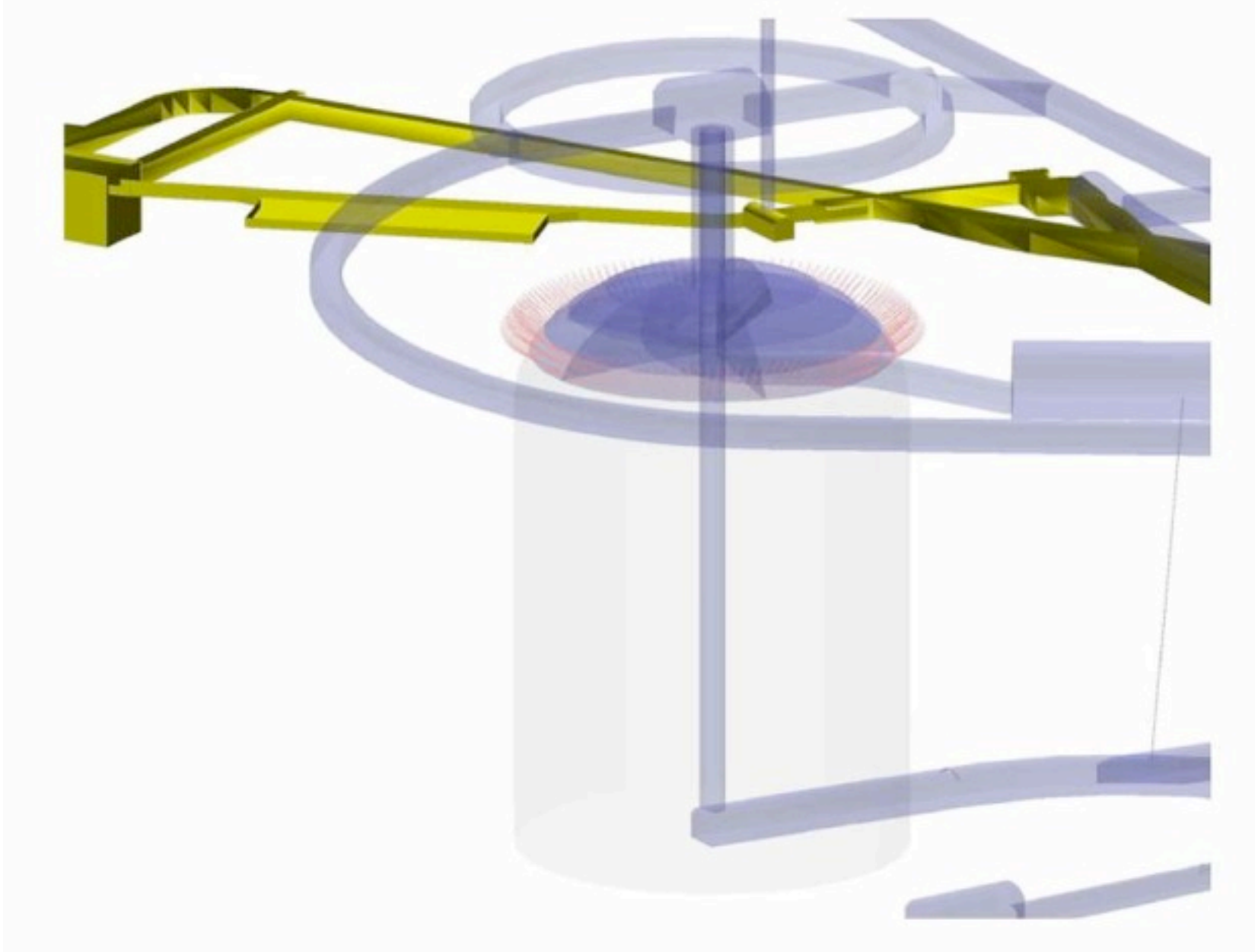


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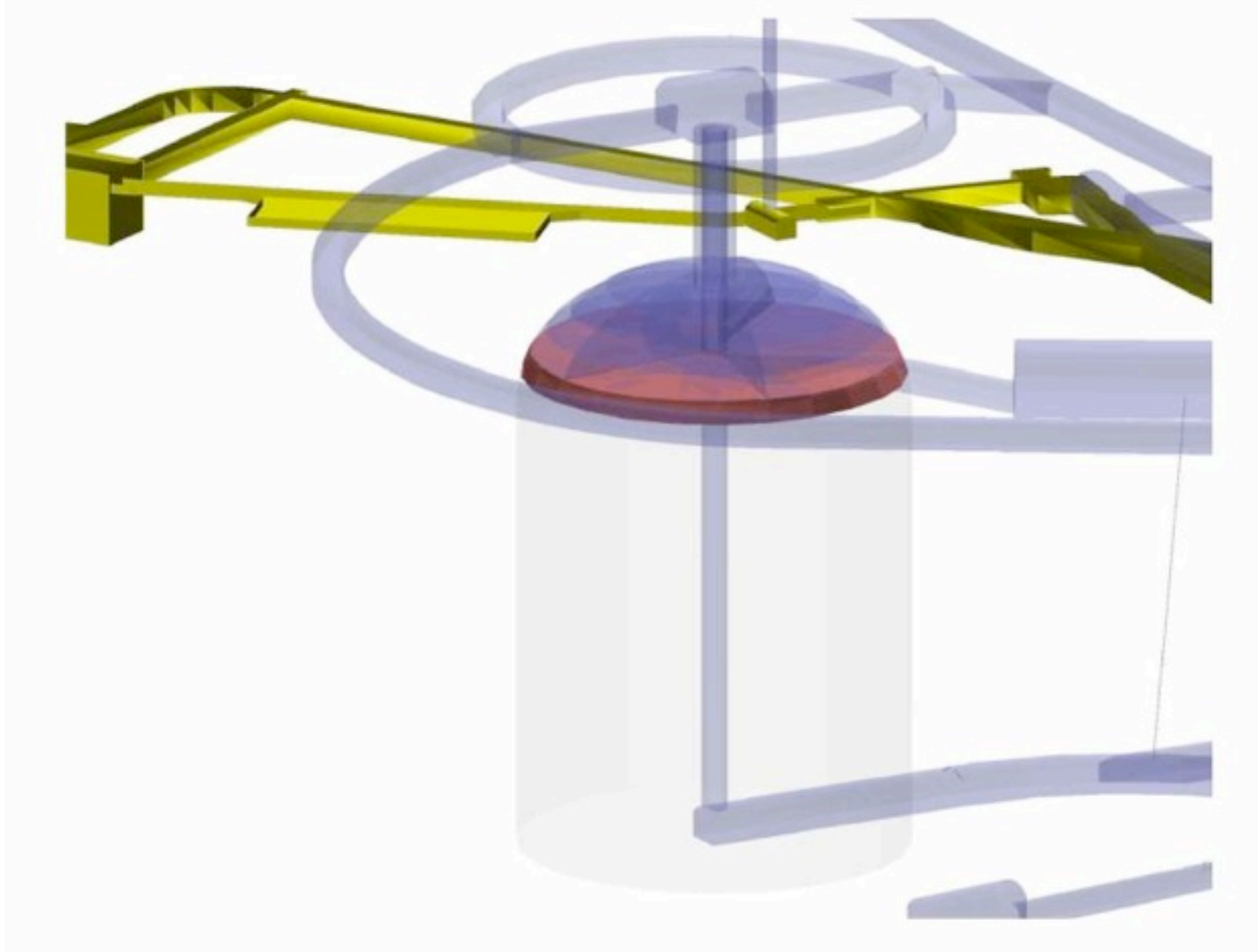


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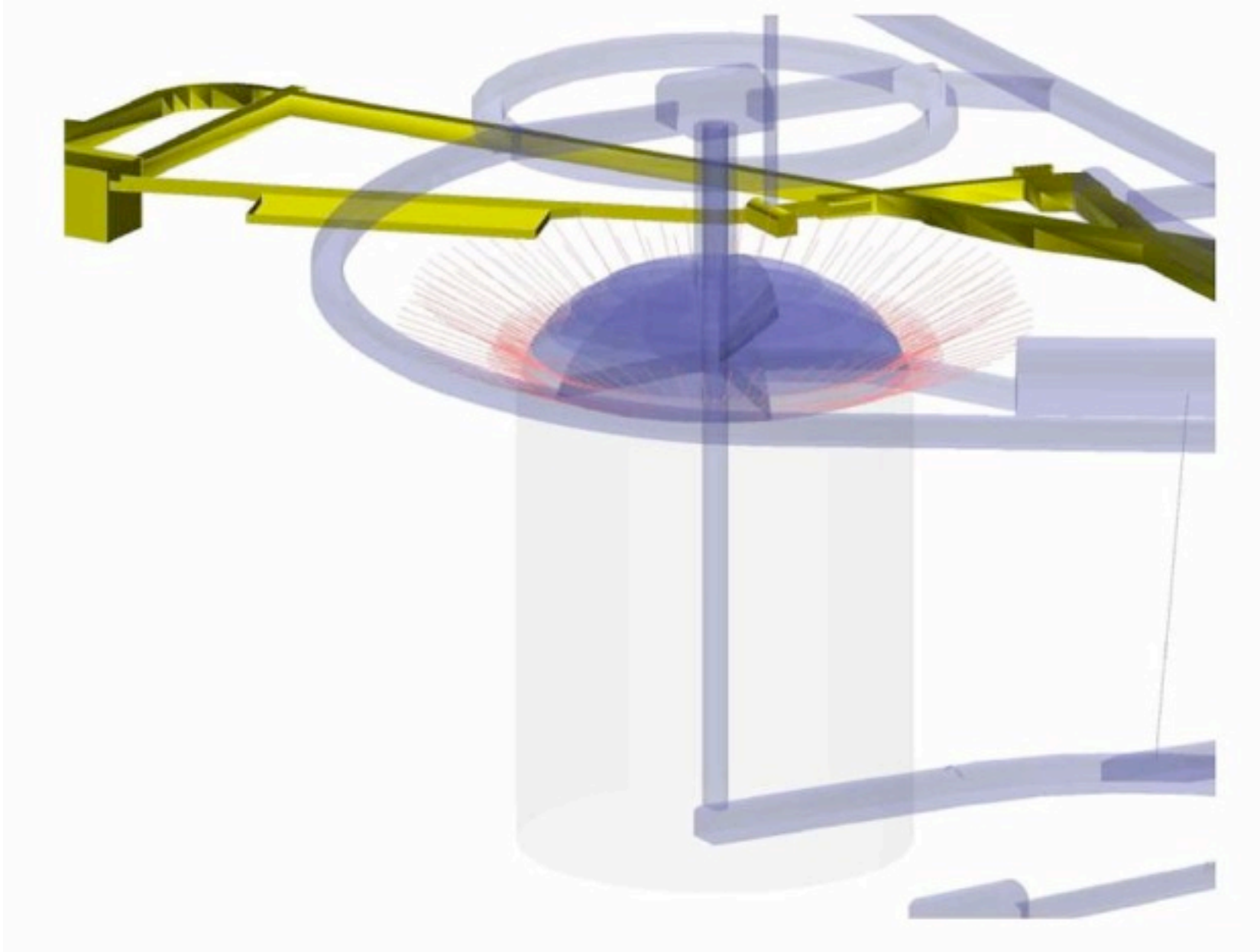


# LC-1 Excavation & Support



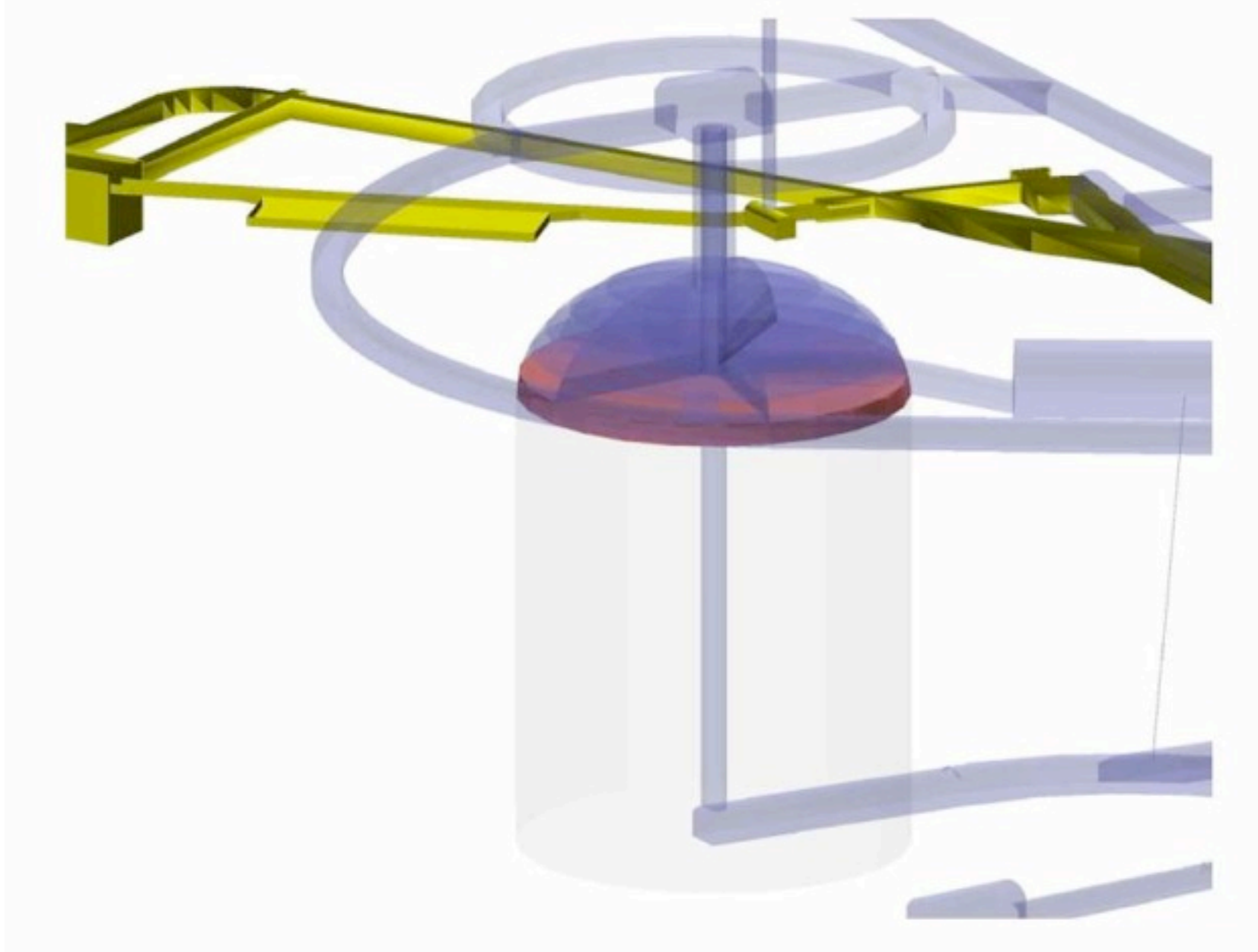


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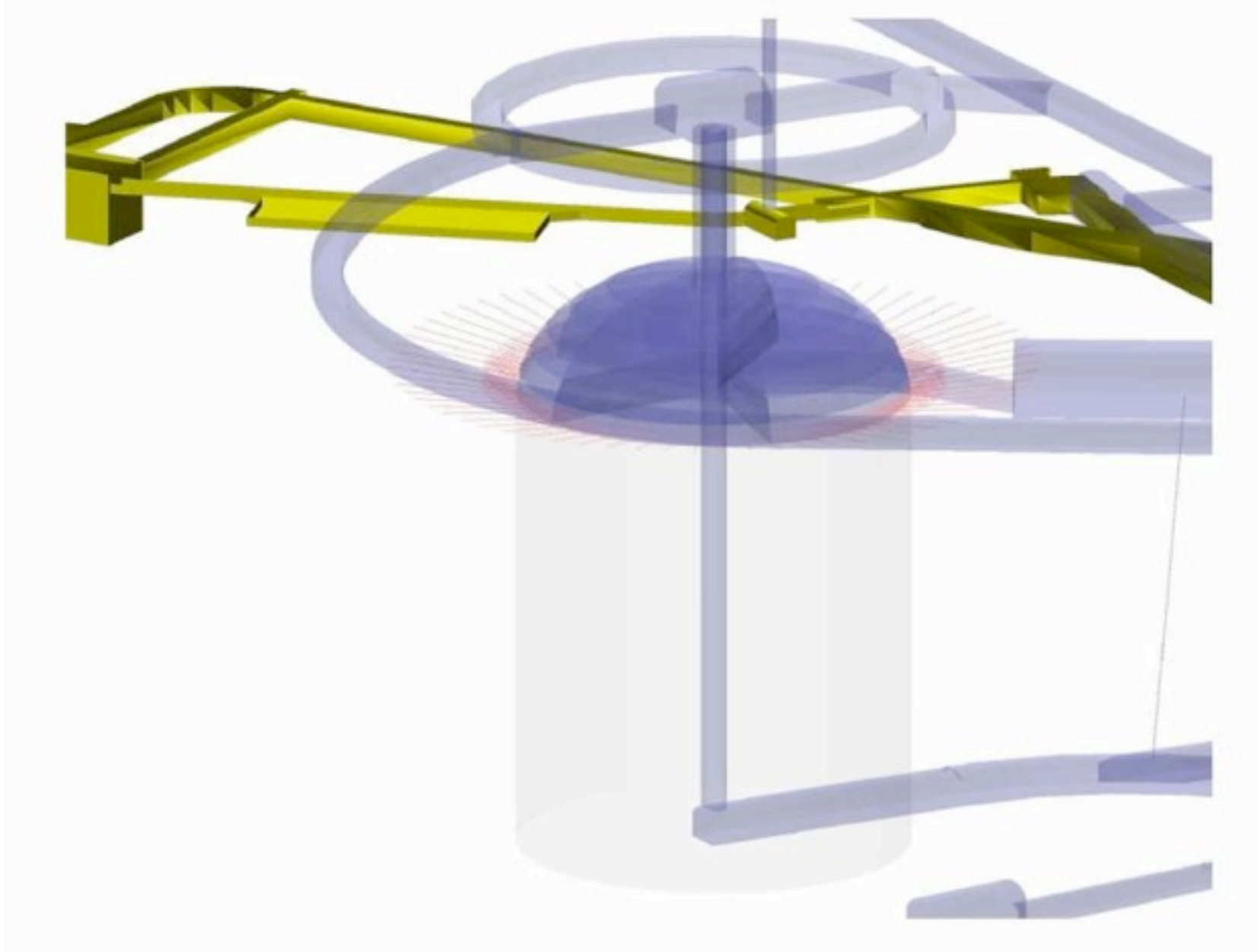


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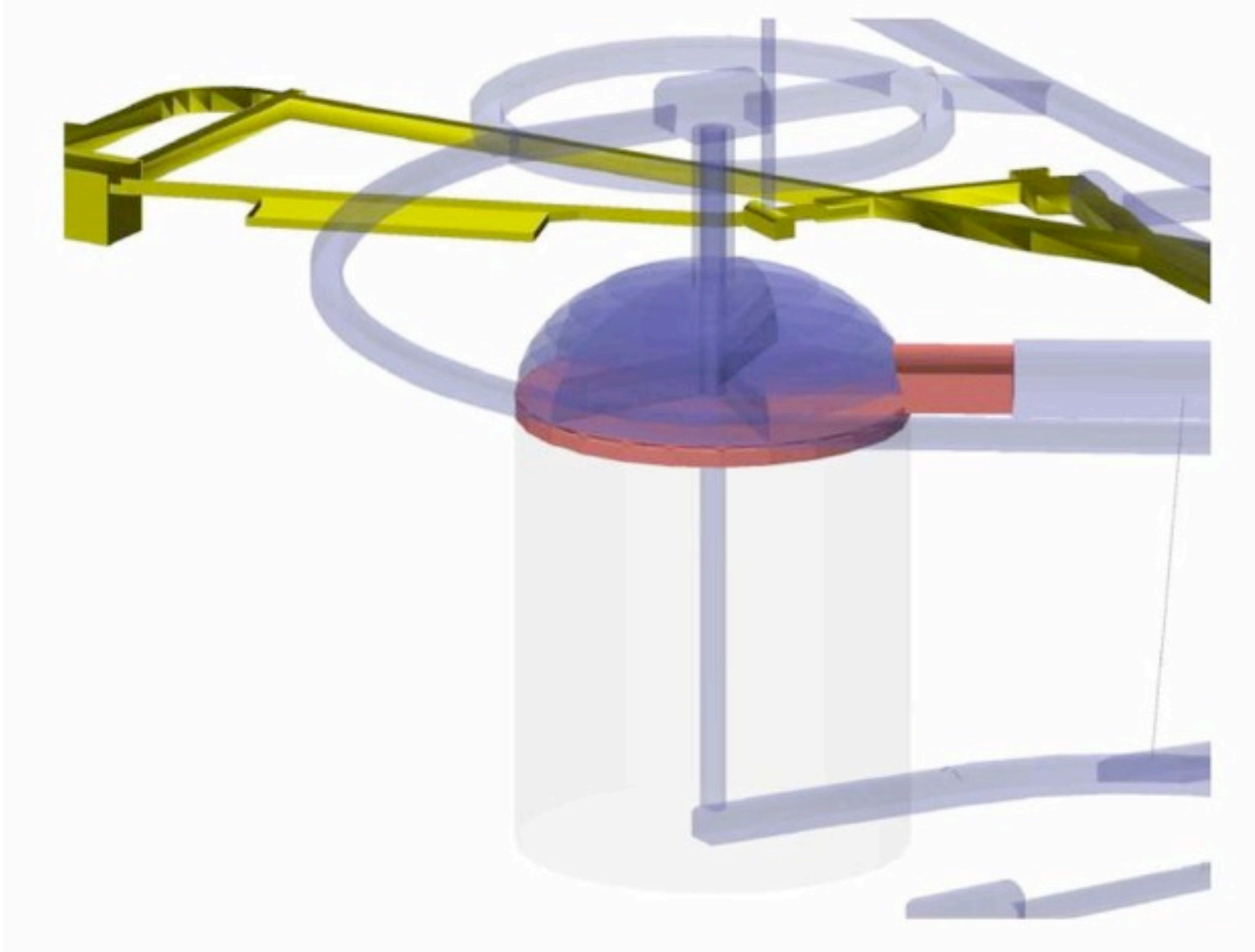


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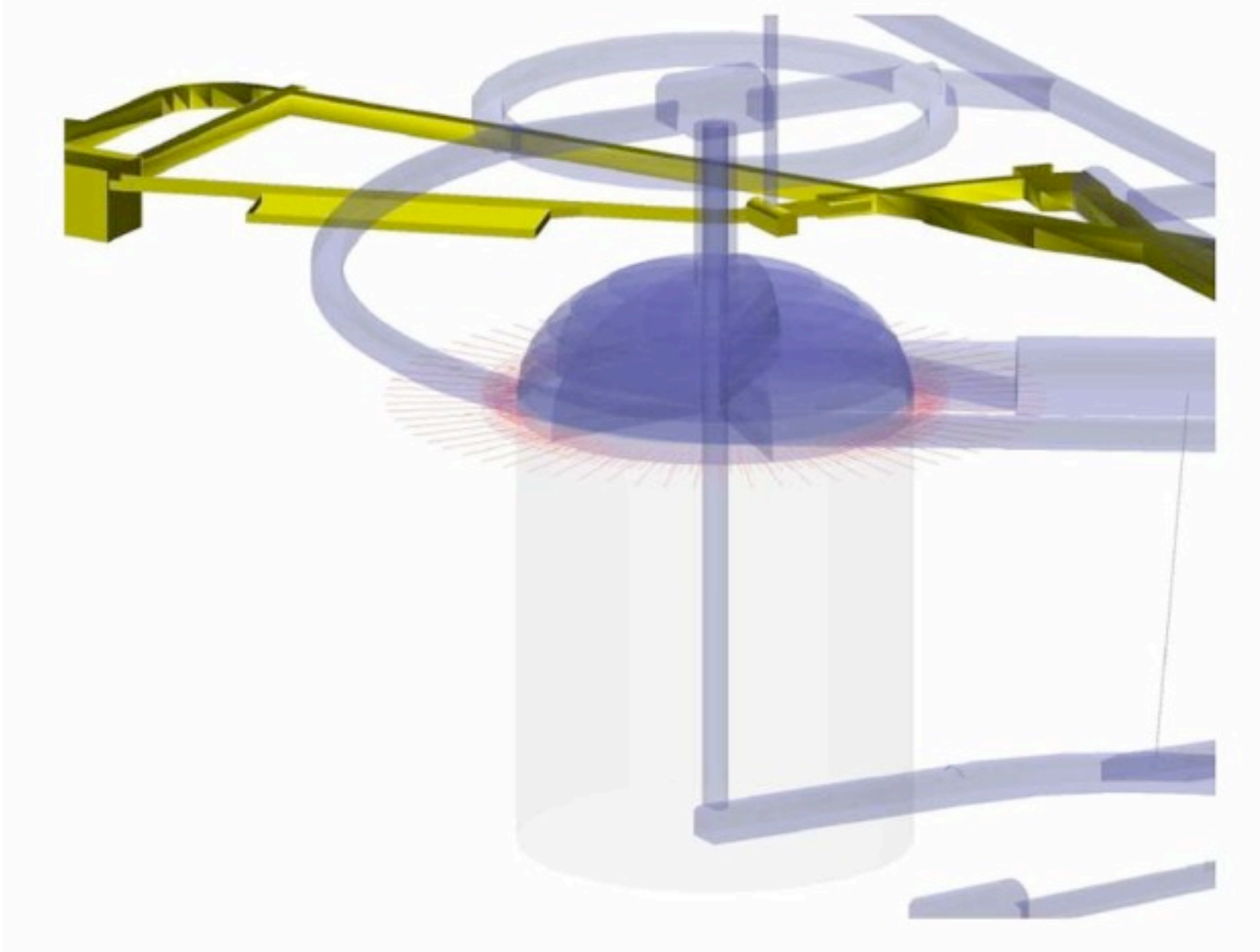


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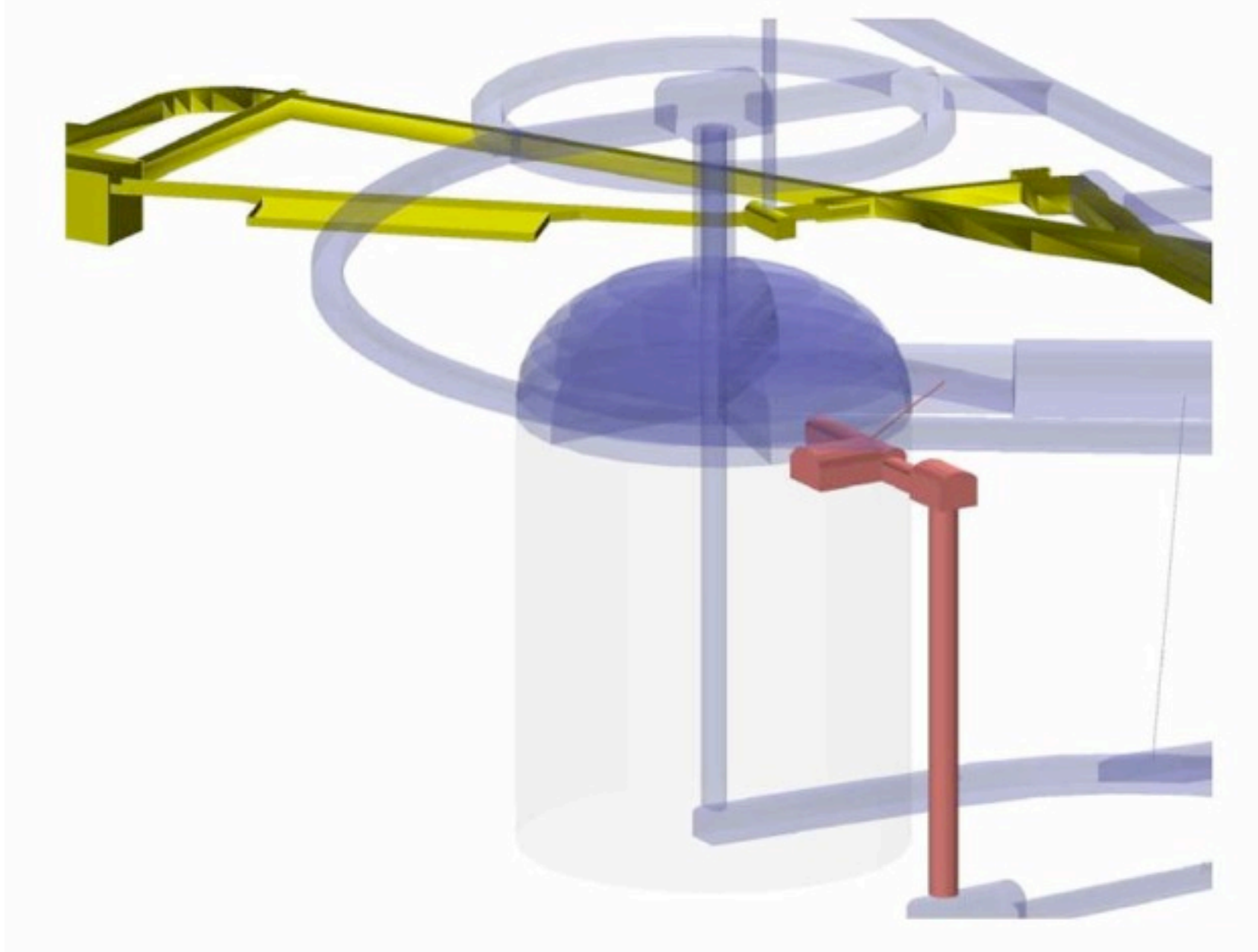


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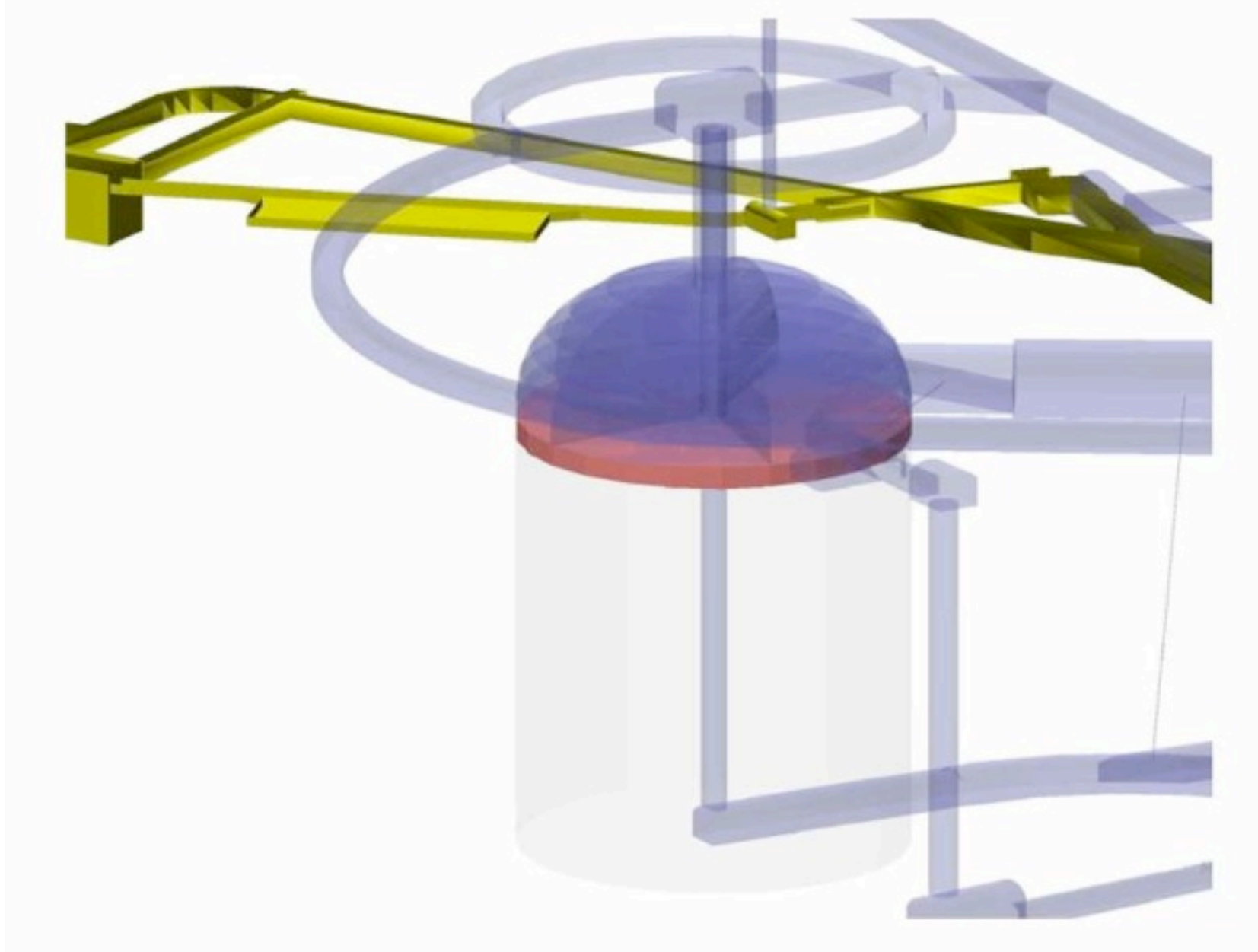


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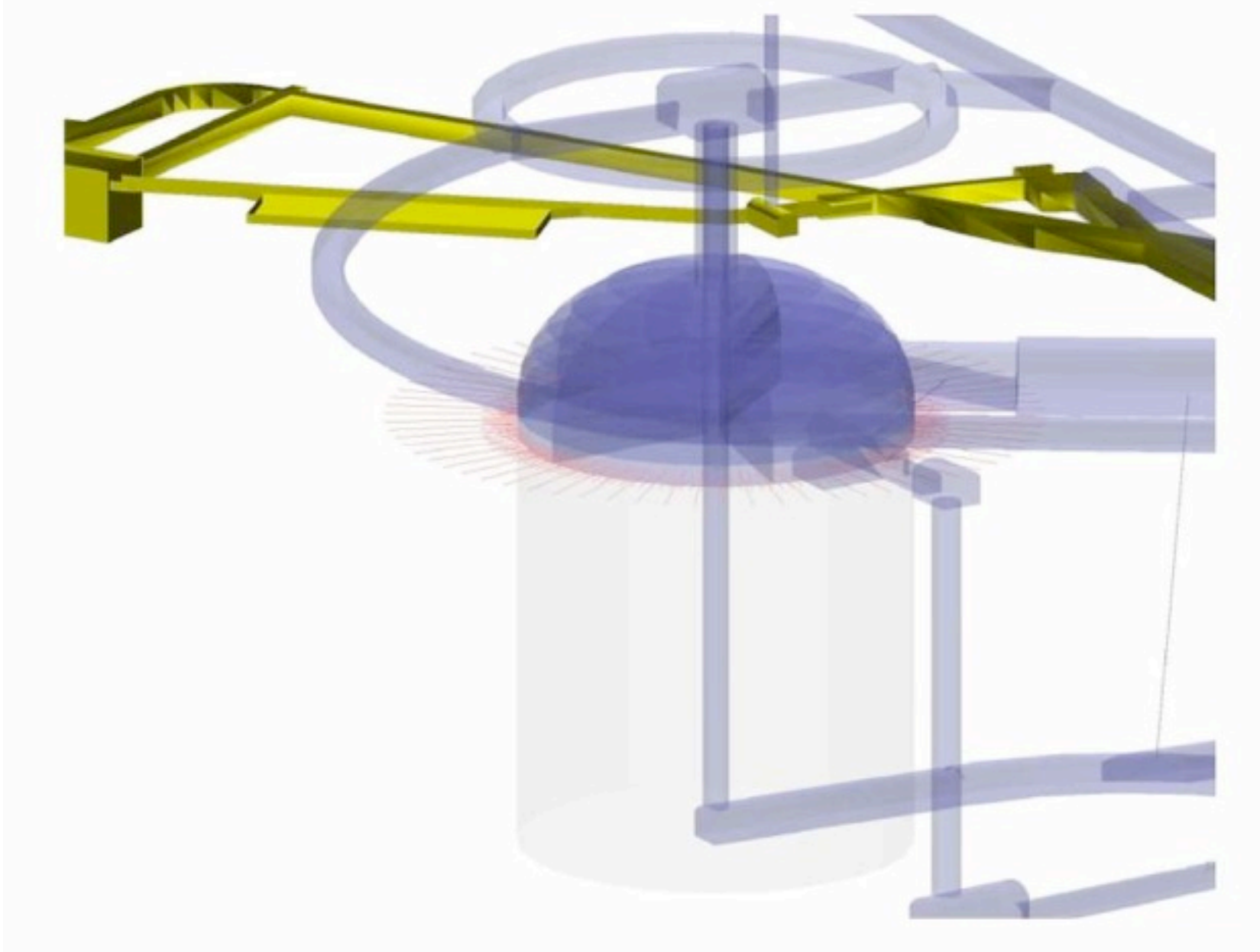


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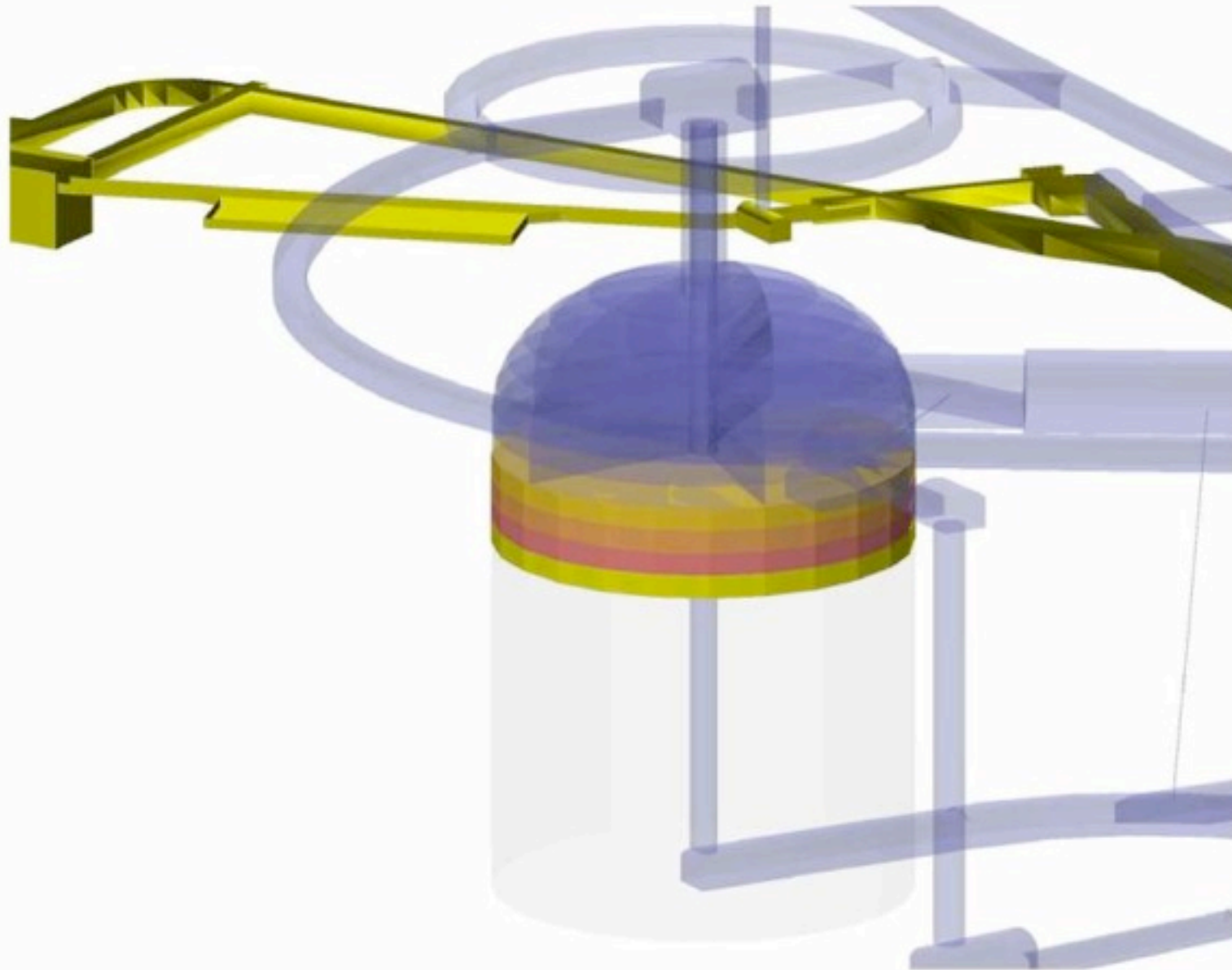


# LC-1 Excavation & Support



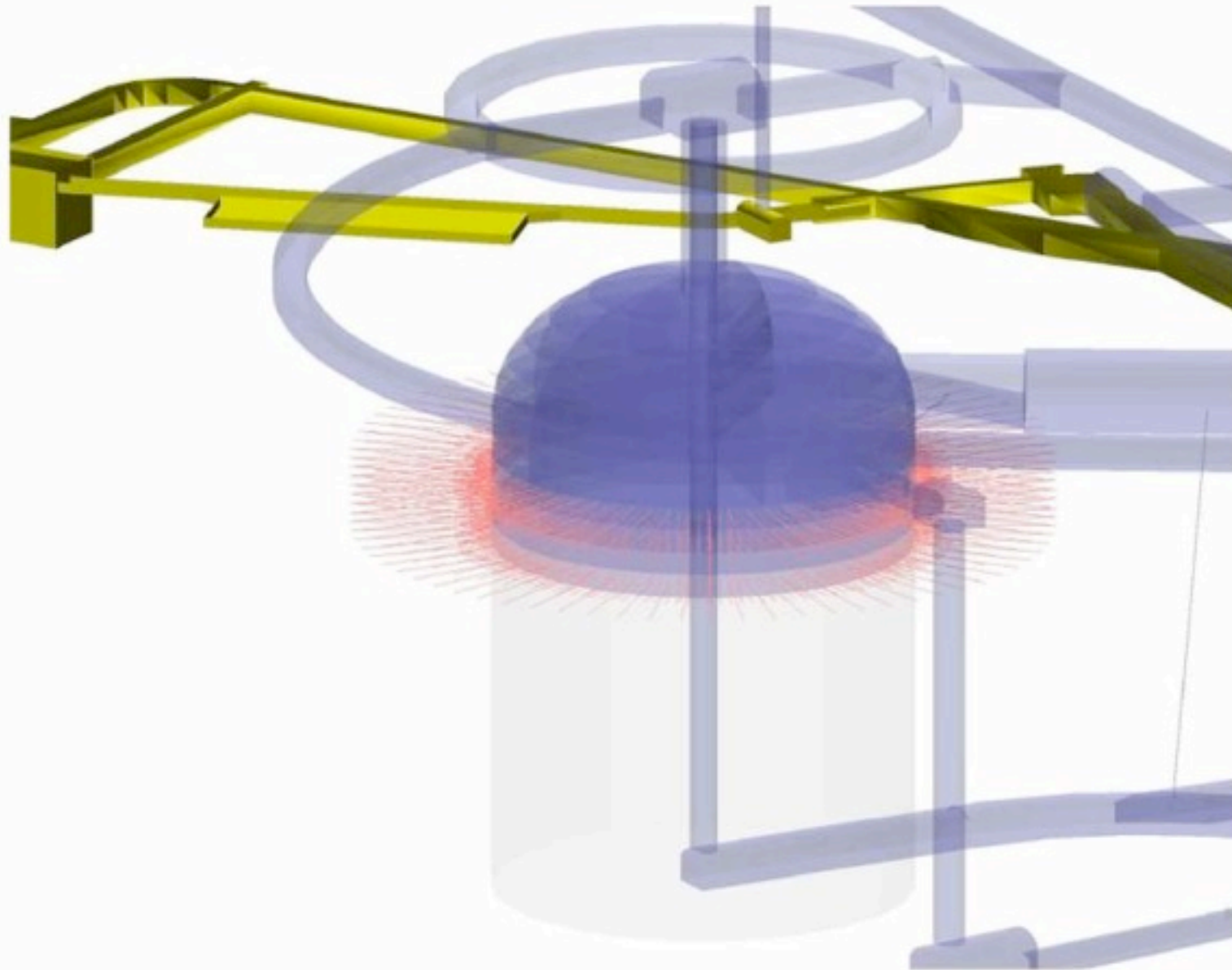


# LC-1 Excavation & Support



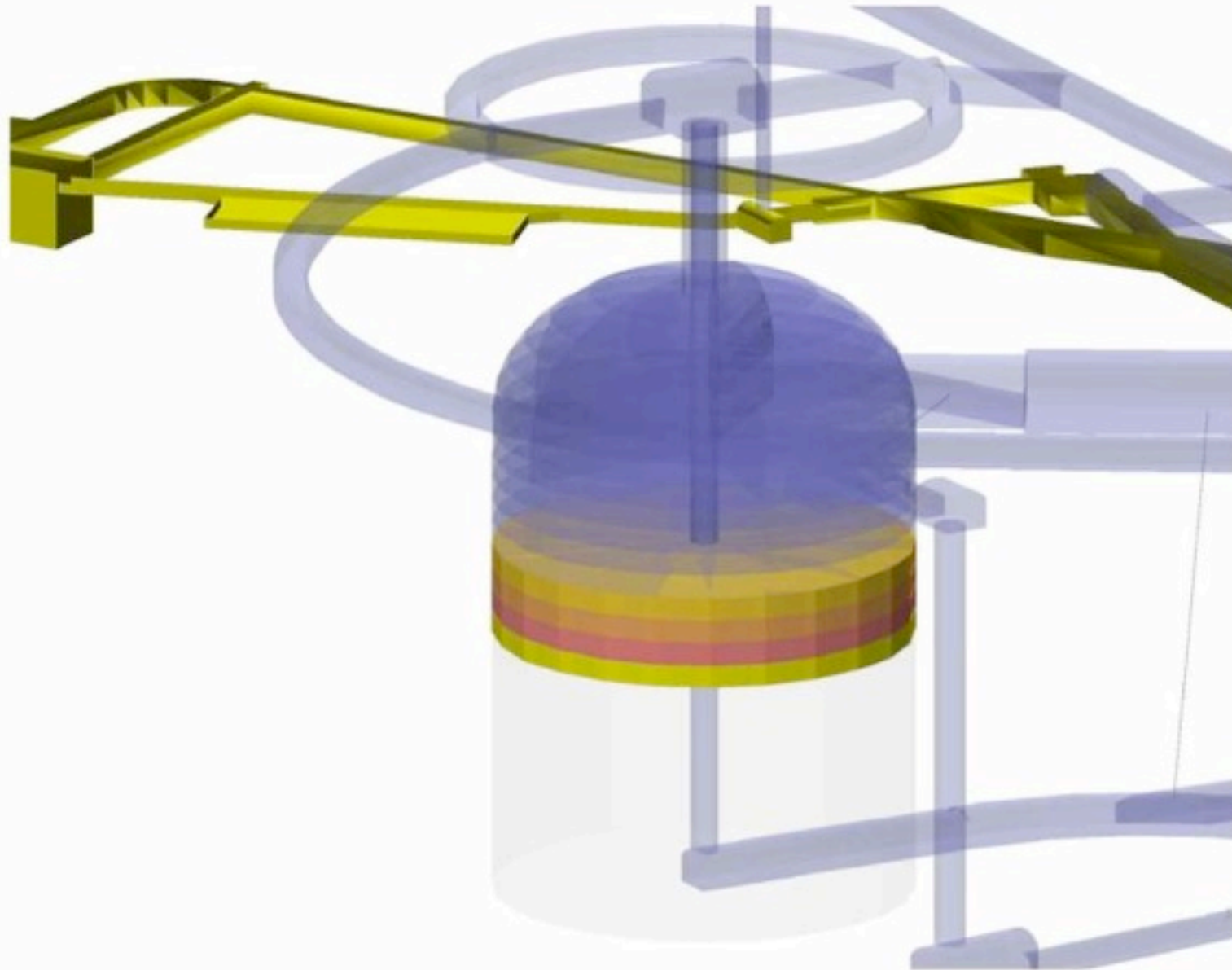


# LC-1 Excavation & Support



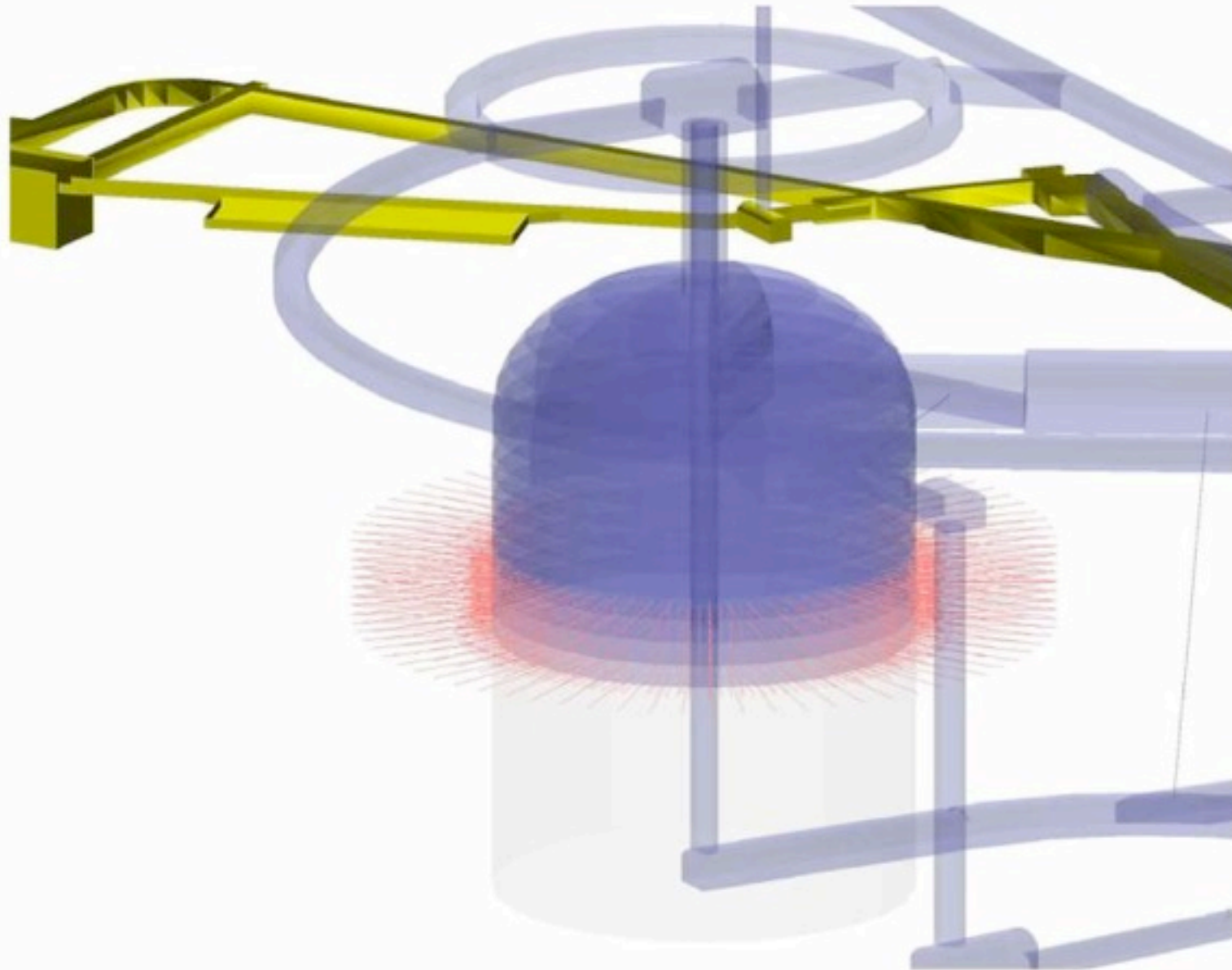


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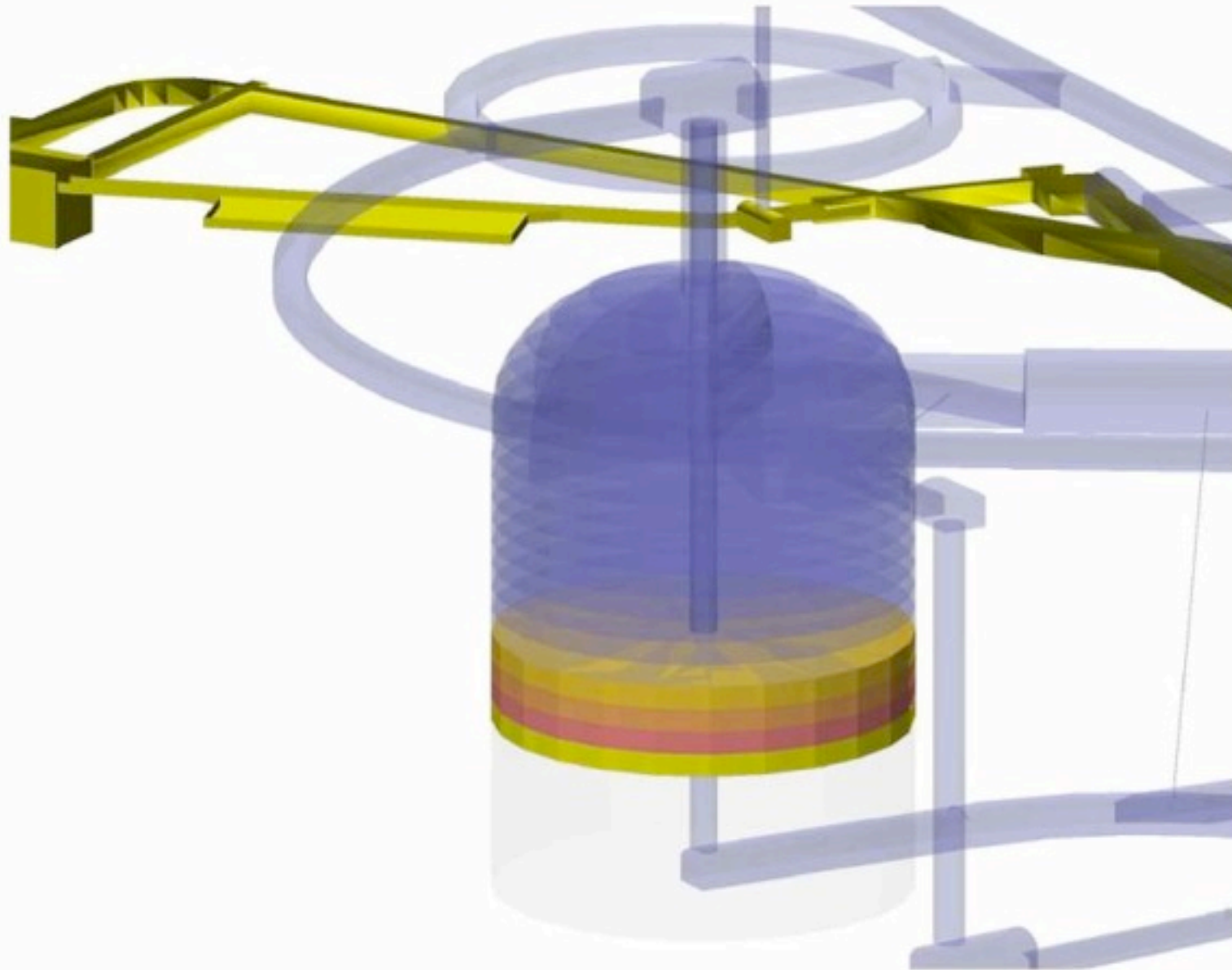


# LC-1 Excavation & Support



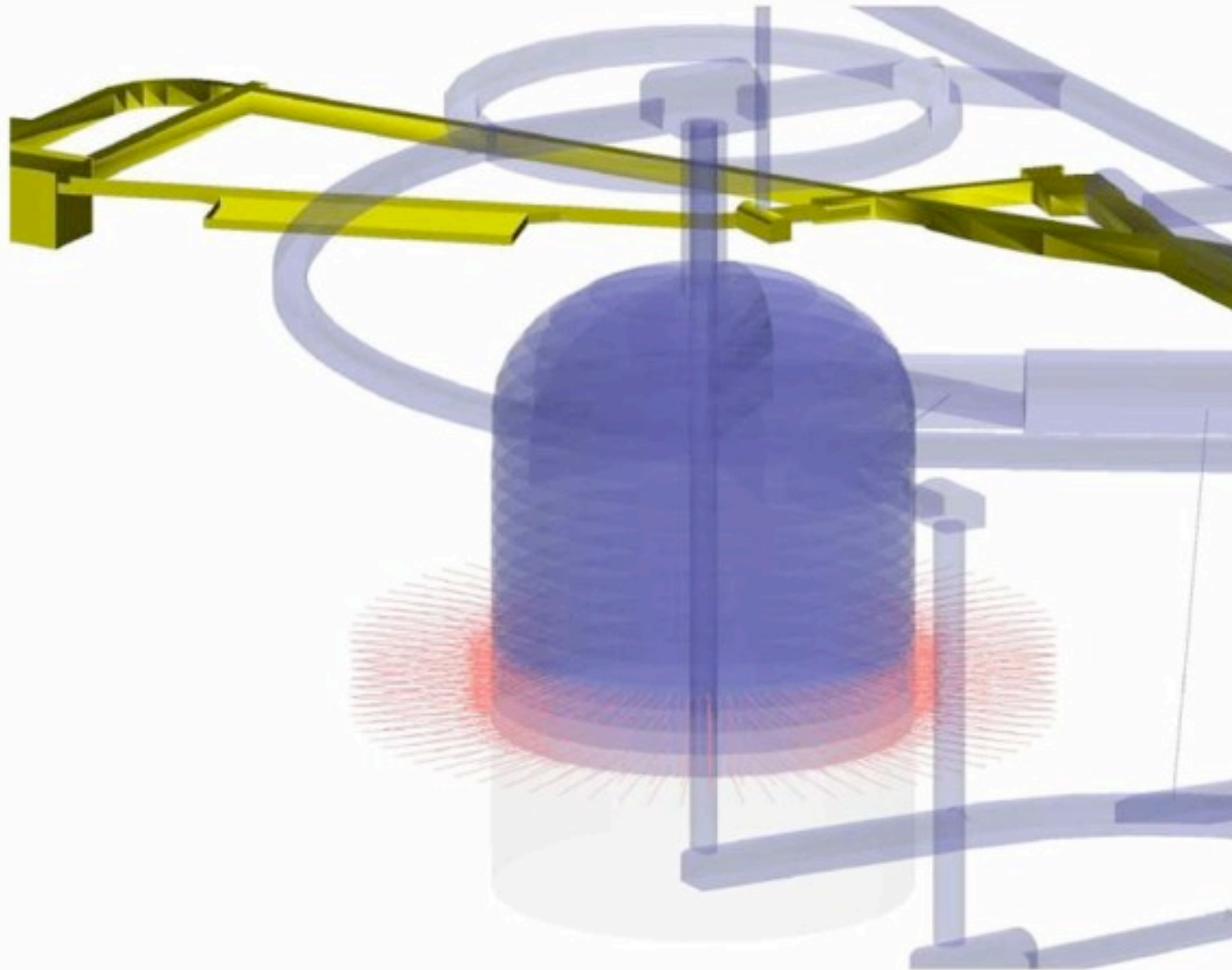


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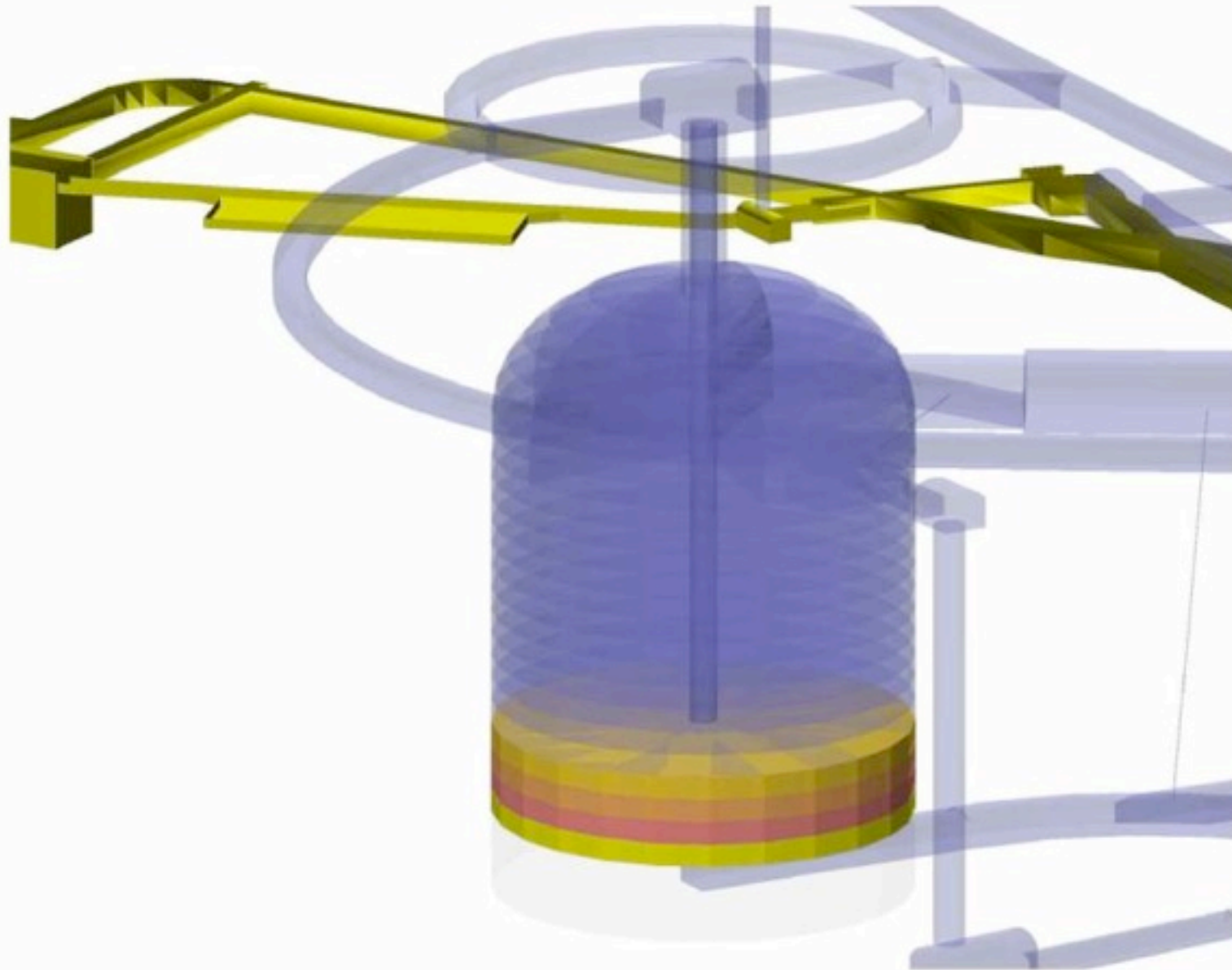


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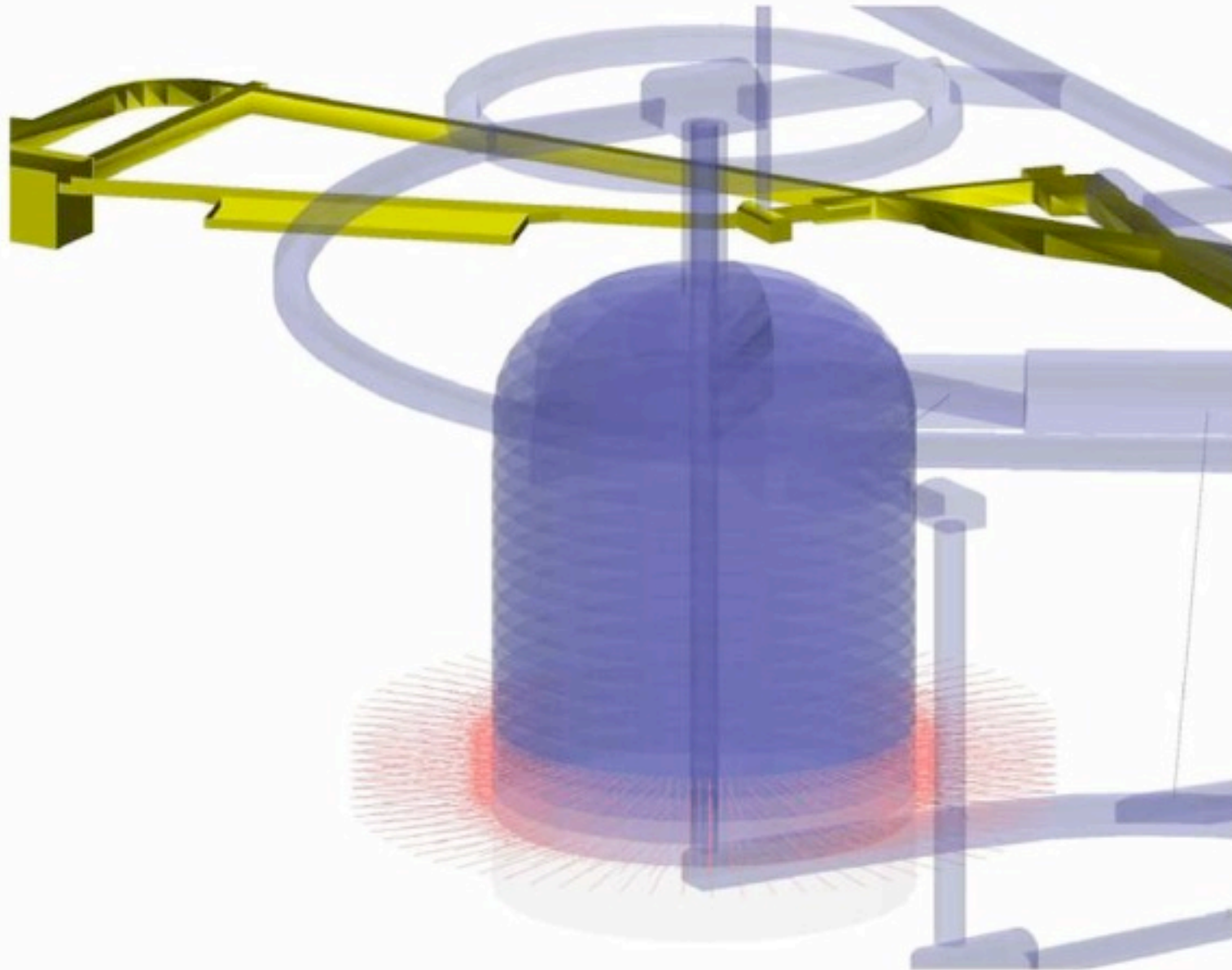


# LC-1 Excavation & Support



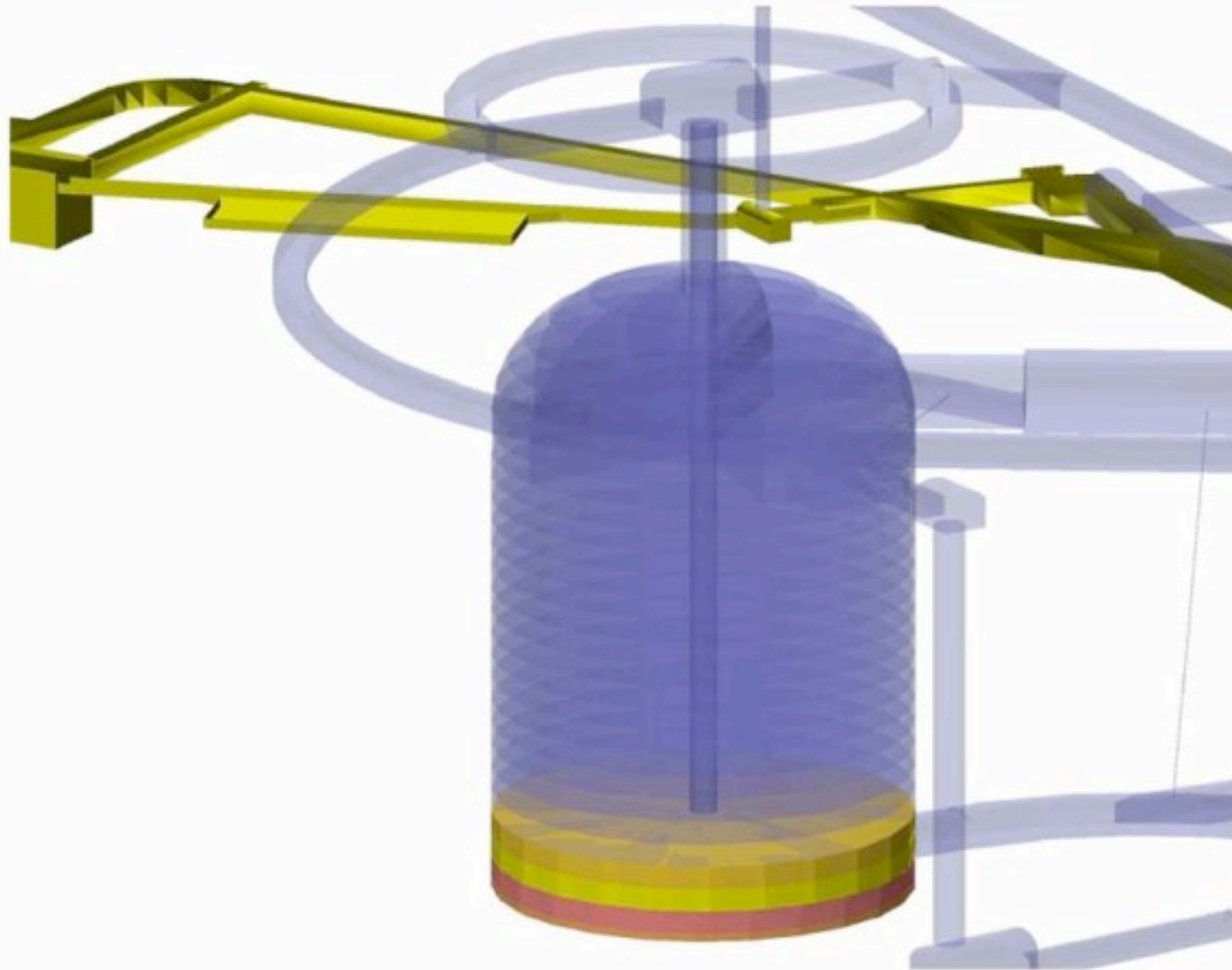


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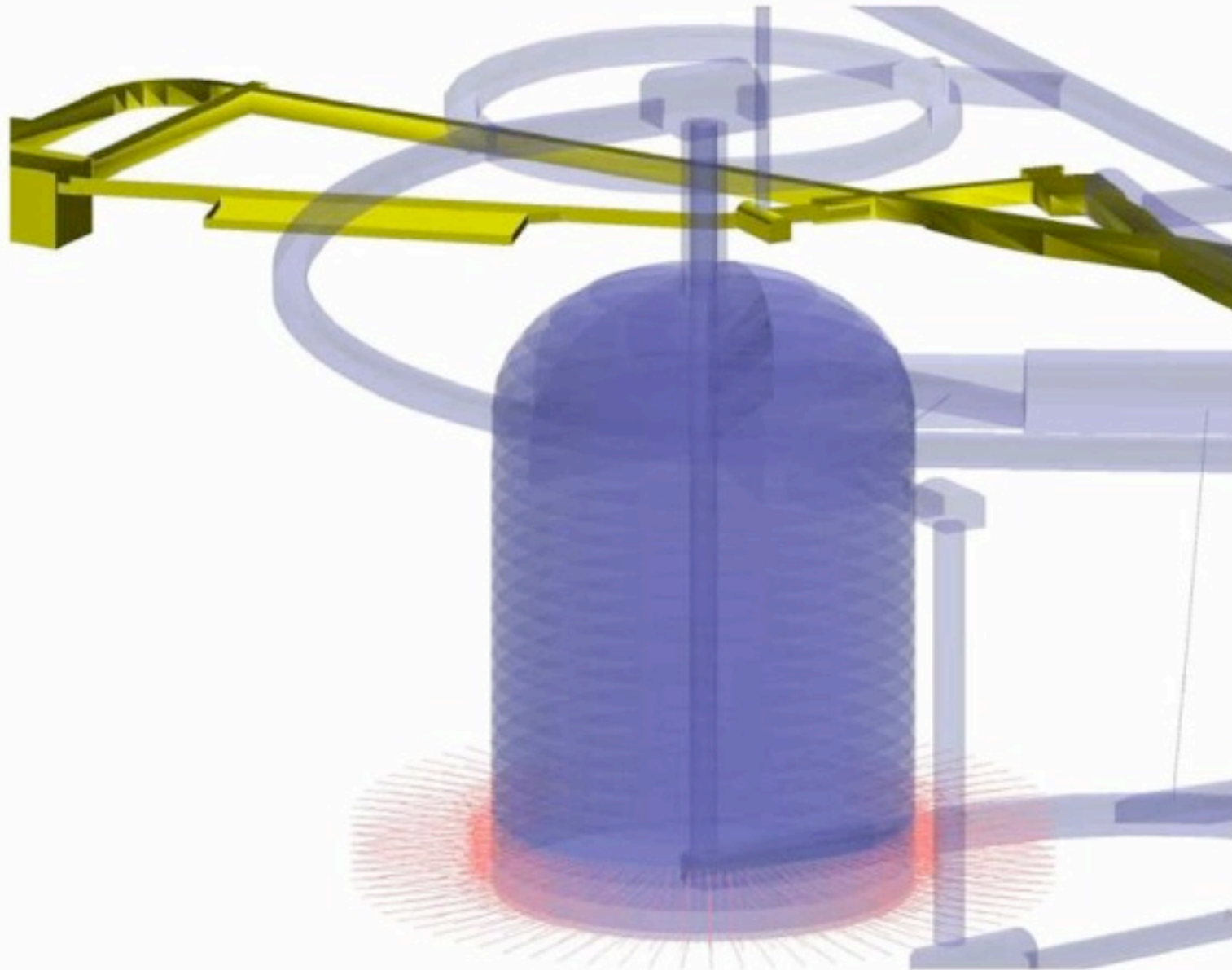


# LC-1 Excavation & Support





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